Assessment of the Influence of Disturbance, Management Activities, and Environmental Factors on Carbon Stocks

Northern Region

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Contents

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1.0 Introduction

Greenhouse gas (GHG) concentrations have increased significantly since 1750 and have greatly exceeded pre-industrial values (IPCC 2007). Human activities such as fossil fuel burning, industrial activities, land use change and agricultural activities are responsible for releasing large amounts of carbon dioxide and other GHGs into the atmosphere. Globally, about half of the emitted GHGs are absorbed by oceans and land, with the remainder staying in the atmosphere for long periods of time (Le Quéré et al. 2015). GHGs trap energy in the atmosphere and cause it to warm. This phenomenon, called the "greenhouse effect", is necessary to sustain life on Earth. However, the large amounts of GHGs humans are releasing to the atmosphere are causing the surface temperature of the Earth to increase with a number of associated large scale changes (NCA 2014), many of which are detrimental to human health and ecosystems.

The Forest Service recognizes the vital role that our nation's forests and grasslands play in carbon sequestration. Carbon sequestration by forests is one way to mitigate GHG emissions by offsetting a portion of those emissions through removal and storage of carbon from the atmosphere. Carbon dioxide uptake by forests in the conterminous United States offset approximately 16 percent of our national total carbon dioxide emissions annually over the last decade (US EPA 2014). Forests and other ecosystems generally act as carbon sinks because, through photosynthesis, growing plants remove carbon dioxide from the atmosphere and store it. However, forests may become sources of carbon dioxide during and after disturbances such as wildfire and timber harvesting. This is usually a temporary effect before the disturbed forests begin to re-grow and resume their function as carbon sinks. Recent estimates of net annual storage indicate that globally and in the U.S. forests are an important carbon sink, removing more carbon from the atmosphere than they are emitting (Pan et al. 2011).

The Forest Service also recognizes that carbon sequestration is one of many ecosystem services provided by forests and grasslands; these include clean water, clean air, biodiversity, wood products, wildlife habitat, food, and recreation. Changes in weather patterns place forest and grassland ecosystems and their services at risk. The National Forest System (NFS) constitutes one-fifth (22 percent) of the Nation's total forest land area and contains one-fourth (24 percent) of the total carbon stored in all U.S. forests, excluding interior Alaska. Thus, management of these lands and disturbance impacts influence carbon sequestration and storage and mitigation of GHG emissions. The future trajectory of carbon stocks on the national forests will be influenced by the variability of conditions and disturbance regimes such as wildfire, insect outbreak, and extreme weather across the U.S.

Sequestration of carbon in US forests is projected to decline over the next 25 years primarily due to land use change and forest aging (Wear & Coulston 2015). There are strong regional differences. For example, the forest carbon sink of the Rocky Mountain region is projected to decline rapidly or change to a net source due to fire, insect outbreaks and aging, whereas Eastern forests which are more intensively managed and lack such widespread disturbances are expected to continue to be carbon sinks for several decades.

Forests are highly dynamic systems that are continuously repeating the natural progression of establishment, growth, death, and recovery, while cycling carbon throughout the ecosystem and the atmosphere. This cycle which drives overall forest carbon dynamics varies geographically and by forest type, and by the frequency, magnitude, and type of disturbance events. Natural and anthropogenic disturbances can cause both immediate and gradual changes in forest structure which in turn affect forest carbon dynamics by transferring carbon between the different ecosystem and atmospheric carbon pools (Figure 1). While disturbances may be the predominant drivers of forest carbon dynamics (Pan et al. 2011), environmental factors, such as the concentration of carbon dioxide in the atmosphere, the availability of key forest nutrients like nitrogen, and climatic variability influence forest growth rates and consequently the cycling of carbon through a forest ecosystem (Pan et al. 2009, Hyvönen et al. 2007). Thus, an accurate and comprehensive assessment of forest carbon stocks and trends and the drivers that influence them must include the effects of both disturbances and environmental factors.

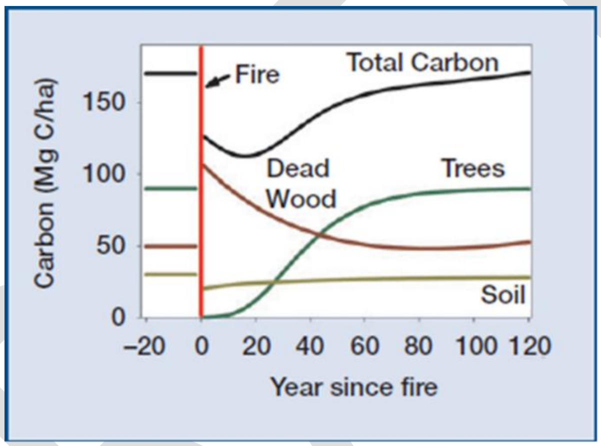

Figure 1. The effect of fire on forest ecosystem carbon pools such as soil, dead wood, etc. Figure from McKinley et al. 2011.

The long-term capacity of forest ecosystems and harvested wood products to sequester and store carbon depends in large part on their health, resilience, adaptive capacity, and utilization of timber (McKinley et al. 2011). Under a changing climate, forests are increasingly affected by many factors such as multi-year droughts, insect and disease epidemics, wildfires, and catastrophic storms (Westerling et al. 2006, Cohen et al. 2016). Maintaining healthy forest structure and composition may not eliminate disturbance, and may in fact entail additional low-magnitude disturbance, but is likely to reduce the risk of large and long-term carbon losses through catastrophic disturbance (Millar and Stephenson 2015). Forest ecosystems capable of adapting to changing conditions will sequester carbon and store it more securely over the long term, while also furnishing woody materials to help reduce fossil fuel use. For forests managed for timber products, it is important to account for the carbon that is retained in harvested wood as well as substitution effects of using wood instead of other energy-intensive materials since these quantities may be large and should not be considered as emitted carbon dioxide (Perez-Garcia 2005).

A first step toward managing healthy forests is understanding how past patterns of disturbance and climate have affected their ecosystem functions such as carbon storage. A nationally consistent carbon assessment framework has been developed for the NFS to deliver forest carbon disturbance information for every region and individual national forest. This assessment builds upon the baseline carbon storage assessments produced for each Region (http://www.fia.fs.fed.us/forestcarbon/default.asp). *The current assessment framework focuses on disturbance effects upon ecosystem carbon, setting aside temporary storage of harvested carbon in product pools.* The sequestration value of harvested wood product carbon is quantified in the existing regional baseline assessments and related analyses have appeared elsewhere (Healey et al. 2009, Stockmann et al. 2014, Anderson et al. 2013). Ongoing work to integrate ecosystem and product life cycle dynamics will allow the sideboards of future Forest Service assessments to expand beyond the ecosystem boundary.

2.0 Purpose of This Assessment

This report expands upon previous assessments of baseline carbon stocks across individual national forests and at the regional-scale by assessing how stocks at those scales are affected by factors such as timber harvesting, natural disturbances, land-use change, climate variability, increasing atmospheric carbon dioxide concentration, and nitrogen deposition. The likelihood of management activities affecting future disturbance rates is not assessed. Such assessments are pursued through stand- and landscape-level risk analysis (e.g. Ager and Finney 2010), and are beyond the scope of this report's goal of assessing the causes of changes in carbon stocks as quantified by carbon monitoring programs such as forest inventories.

Existing guidelines for considering forest carbon are found in various Forest Service policies, programs, and activities such as the 2012 Planning Rule and directives, National Roadmap for Responding to Climate Change , Climate Change Performance Scorecard, Ecosystem Restoration Policy and Directive (FSH 2020), other internal guidance for planning and project-level decisions, and in several State & Private Forestry programs.

The information in this carbon assessment directly supports NFS units in making measurable progress on Climate Change Performance Scorecard Element 9 (Carbon Assessment and Stewardship), while helping forests meet carbon assessment requirements of the 2012 Planning Rule and directives.

Scorecard Element 9 poses the following questions:

> ***Does the Unit have a baseline assessment of carbon stocks and an assessment of the influence of disturbance and management activities on these stocks? Is the Unit integrating carbon stewardship with the management of other benefits being provided by the Unit?***

The baseline assessments of carbon stocks were produced in early 2015 using the Carbon Calculation Tool (CCT) and the Forest Inventory and Analysis and harvested wood products data. The baseline assessments (found here) meet the intent of assessing observed trends but are limited in ability to reveal detailed causes.

The expanded assessments reported here answer the second part of the first question by integrating two additional forest carbon models: 1) Forest Carbon Management Framework (ForCaMF) (Healey et al. 2014 and 2016) and 2) Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen et al. 2000, Zhang et al. 2012), to calculate the relative impacts of disturbance (e.g. fires, harvests, insect outbreaks, disease) and non-disturbance factors (climate, nitrogen deposition, carbon dioxide concentrations). Results of these expanded assessment will help forest managers quantify carbon outcomes of broad forest management strategies and project-level decisions, separated from the effects of factors that are beyond the control of land managers.

Using the baseline and expanded assessments, and the draft Forest Carbon Principles outlined below, NFS units can begin to integrate carbon stewardship thinking and practices within management activities, thus helping to address the final question of Scorecard Element 9 – Is the Unit integrating carbon stewardship with the management of other benefits being provided by the Unit? This requirement could be accomplished through use and application of available information related to carbon through the land management planning process, program guidance, forest plans, project plans and analyses, or other strategic program planning. Units are encouraged to review the Scorecard Guidance, including Scorecard Appendix F.

Units can apply this data in their forest management planning and practices by asking questions including, but not limited to –

- Is the land management plan area sequestering and storing carbon in the recent past, or emitting stored carbon?
- How have disturbances, projects, and activities influenced carbon stocks (including harvested wood products) in the past and may affect them in the future?
- Are existing conditions and trends of forest vegetation and soils indicating that the plan area is a carbon sink or carbon source?
- Under existing plan guidance and alternatives being considered, what is the likely future trend of the plan area in sequestering and storing carbon, including in harvested wood products?
- What is the risk of loss to carbon storage due to potential disturbance factors?
- Are there opportunities to change plan components to influence these trends?

These expanded assessments are produced following methods described in several cited source documents.

Forest Carbon Principles

Forest carbon management (carbon stewardship) may best be articulated through the following draft principles and guidelines. They are intended to provide considerations for integrating carbon management with planning and implementation processes and with efforts to adapt forests to the impacts of a changing climate. These are preliminary guiding principles intended to be refined, updated and formally approved based on field experience, emerging science and interpretation across the full range of Forest Service programs and authorities.

1. **Emphasize ecosystem function and resilience.** Carbon sequestration capacity depends on sustaining and enhancing ecosystem function to maintain resilient forests adapted to changing climate and other conditions.
2. **Recognize carbon sequestration as one of many ecosystem services.** Carbon sequestration is one of many benefits provided by forests, grasslands, and forest products, now and in the future. Carbon sequestration should be considered in context with other ecosystem services.
3. **Support diversity of approaches in carbon exchange and markets.** Recognize that decisions about carbon in America's forests are influenced by ownership goals, policy, ecology, geography, socioeconomic concerns, and other factors that vary widely.
4. **Consider system dynamics and scale in decision making.** Evaluate carbon sequestration and cycling at landscape scales over long time frames. Explicitly consider uncertainties and assumptions in evaluating carbon sequestration consequences of forest and grassland management options.
5. **Use the best information and methods to make decisions about carbon management.** Base forest management and policy decisions on the best available science-based knowledge and information about system response and carbon cycling in forests, grasslands, and wood products. Use this information to deal directly with uncertainties, risks, opportunities, and tradeoffs through sound and transparent risk management practices.

Note: These draft principles are not meant to imply that maximizing forest carbon storage should be the objective of any forest plan or that carbon should be the most important or overriding purpose of forest plans or project actions. This information is provided to help forests and their stakeholders determine the state of the carbon resource, and how carbon stewardship might be blended with other ecosystem service goals in planning and management.

3.0 Forest Carbon Management and Stewardship

The Forest Service is leading the government in the national conversation and action on forest carbon. The basic approach we employ is managing carbon through managing the health and productivity of the nation's forests. Our work focuses on managing risks to the health, productivity and ability of the resource to provide the goods and services called for in the management plan. Management actions have carbon outcomes and those are considered among the benefits being managed. Forest systems are dynamic and emit and capture carbon regardless of human intervention. Our carbon strategy is embedded in a larger adaptation strategy for managing the resource considering multiple impacts of natural and anthropogenic stressors.

Carbon management is an aspect of sustainable land management. Our job is to maintain the long term health and productivity of forests and grasslands to maintain a flow of all of their benefits. Carbon adds another dimension to our work. There will be both tradeoffs and synergies between carbon flows and other services, and balancing these interactions will continue to be part of our resource management mission *(see draft Forest Carbon Principles).*

Our goal is to manage system vulnerability to multiple stressors through adaptation and mitigation activities. We champion the principles of considering carbon and other benefits flowing from forests, integrating climate adaptation and mitigation, and balancing carbon uptake and storage among a wide range of ecosystem services. We are also striving to provide for social, economic, and ecological sustainability.

Forest management strategies we use include retaining and protecting forest land from conversion to non-forest uses; restoring, maintaining, and enhancing resilient forests that are better adapted to a changing climate and more resistant to catastrophic wildfires and other stressors; and reforesting lands impacted by catastrophic wildfires and other disturbances. Other strategic management options for reducing greenhouse gas emissions include changes in land management, afforestation (and other land use changes), avoiding loss of forest land, adding to the harvested wood products pool, and bioenergy *(see* Scorecard Appendix F.*).*

4.0 Regional Description – Northern Region

The Northern Region (Region 1) consists of 11 National Forests spread across four states including northwestern South Dakota, Montana, northern Idaho, and northeastern Washington (Figure 2). These National Forests include Custer, Gallatin, Lewis and Clark, Beaverhead-Deerlodge, Helena, Lolo, Flathead, Bitterroot, Nez Perce-Clearwater, Kootenai, and Idaho-Panhandle. The analysis of factors contributing to carbon stocks and trends was conducted on only the forested areas of these National Forests, thus National Grasslands such as the Dakota Prairie Grasslands in North Dakota was not included. Also, to restrict the analysis to only lands managed by the U.S. Forest Service, any private inholdings within National Forests boundaries were excluded.

The history of Euro-American settlement, land use, and policies provide useful context for understanding regional forest carbon trends indicated by the inventory and assessment results. While Euro-American settlement first expanded into the Northern region in the early-1800s, it was not until the mid-to-late-1800s that the major influx of permanent settlers arrived and began altering the landscape. In the 1880s, large areas of land, typically in valleys, were cleared for agriculture, settlements, and railroad expansion. By the 1890s, the completion of the railroad opened up new, national markets enabling the region's forest products industry to grow, and also brought more settlers to the region. Although timber harvesting began on a small scale in the late 1800s and continued to expand and intensify through the early 1900s (Baker et al. 1993), it was not until the 1940s that the Northern Region experienced large-scale logging operations on National Forest lands. Harvest volumes in the Northern Region greatly declined by the 1990s (Stockmann et al. 2014).

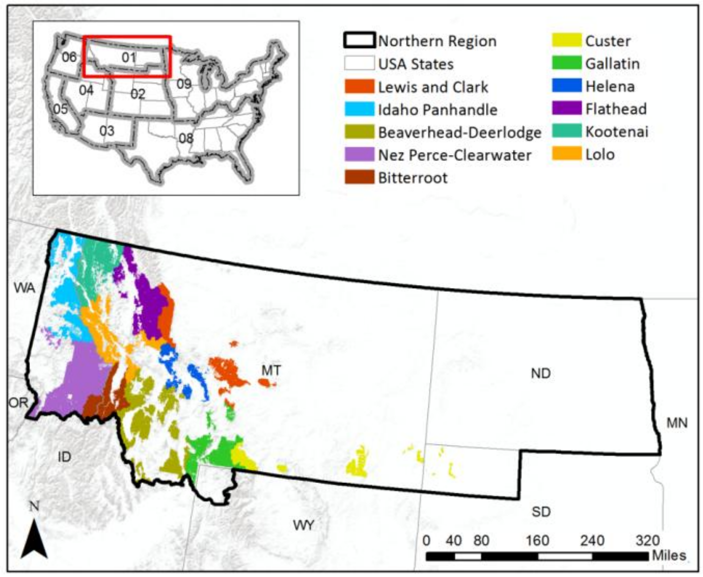

Figure 2. Map of the Northern Region (also referred to as Region 1 or R1).

In addition to timber harvesting, the forest carbon legacy of the Northern Region is also tied to its history of fires and fire management. For instance, thousands of acres of the region's forests were burned by large fires in 1889, prior to the organization of a firefighting system and watch towers. After the devastating 1910 fire season that left some 3 million acres of forest land scorched in Idaho and Montana, fire protection came into the forefront of Forest Service policies. The Forest Service introduced a national fire suppression policy, which entailed intensive efforts to prevent, detect, and suppress all wildfires (Pyne 1982, Baker et al. 1993). A policy shift from fire control to fire management in the 1970s enabled natural fires to burn across landscapes where considered safe and appropriate, in an attempt to restore historical fire regimes (Pyne 1982).

Both land use history and recent climatic changes have led to large and intense disturbances in the Northern Region over the past few decades. The Northern Rockies have experienced increases in large wildfires, occurring over longer durations and longer fire seasons, much of which is due to warming temperatures and droughts (Westerling et al. 2006). Over the past few decades, severe bark beetle outbreaks affecting several dominance types caused widespread tree mortality, reducing forest carbon uptake and increasing future emissions from the decay of killed trees (Kurz et al. 2008). The land use and disturbance legacy and the recent disturbances in this region provide important background for understanding past and current forest carbon dynamics.

5.0 Methodology, Uncertainty and Results

5.1 Forest Carbon Management Framework

5.1.1 Methodology

The Forest Carbon Management Framework (ForCaMF) takes advantage of corporate Forest Service monitoring data, management records and management tools, complemented with forest change information from the Landsat series of satellites, to provide forest-level assessments of the impact of different kinds of disturbance on ecosystem carbon storage. **These assessments take the form of estimation of how much more carbon would be on each national forest if disturbances that took place from 1990 to 2011 had not occurred.** Specifically, the impact of disturbance factor *F* (e.g., harvest, fire, insects, or disease) is estimated as the difference, D_F, in the landscape's non-soil carbon (C) stocks between a scenario where no disturbances occur (*N*) during the observation period and a scenario where <u>only</u> factor *F* occurs (eq. 1).

Eq. [1.]

Each scenario includes simulation of normal density-dependent tree mortality that is not attributable to disturbance. An estimate of D_F is produced for every year, considering the impact of all disturbances that occurred from 1990 to that date. D_F is a function of mapped starting conditions and disturbance history across 10-hectare sections of the landscape (*i*) that share the same starting conditions and disturbance patterns. These sections are called "simulation units" because they are the base units of error simulations described in the next section, but they are also ForCaMF's finest level of carbon accounting. D_F is summed across all simulation units to produce a national forest-scale assessment of disturbance impact (Eq. 1).

The starting point for ForCaMF analysis is mapped records of disturbance and harvest activity across each national forest from 1990 to 2011. These disturbance maps, which are also used by the Integrated Terrestrial Ecosystem Carbon model (Section 5.2), were created by manually editing initial maps created by the automated Vegetation Change Tracker algorithm (Huang et al. 2010). Editing was conducted at the pixel level to align mapped disturbances with several independent data sources: the multi-agency Monitoring Trends in Burn Severity (MTBS) database of fires over 405 hectares (Schwind et al. 2010); multi-temporal composites of Landsat data transformed to one-band per year with the Disturbance Index (Healey et al. 2005); high-resolution time series of aerial imagery served through Google Earth; a combination of a tabular database (Forest Activity Tracking System – FACTS) of historical harvest activities and a spatial database (FACTS spatial) that provides an associated spatial representation of activity locations; (Johnson and Wittwer 2008). These maps do not include information about root disease, which is thought to be an important successional influence throughout much of the Northern Region (Byler and Hagle 2000), because disease frequently does not typically produce large, visible mortality events. Instead, ForCaMF made use of FIA estimates and the expertise of forest pathology and silviculture specialists within the region to determine appropriate levels of root disease to simulate (Healey et al., 2016). Disturbance history from this and the mapping effort, combined with mapped historical forest type and standing live carbon, determined the observed stand dynamics (stand conditions over time and as a function of disturbance history) from 1990 to 2011 in each simulation unit (*i*).

The C storage associated with mapped stand dynamics is obtained by combining the representative field sample measured by the Forest Service's Forest Inventory and Analysis (FIA) program with the Forest Vegetation Simulator (FVS – Crookston and Dixon 2005), a growth model that allows projection of non-soil C stocks (Reinhardt and Crookston 2003) under a variety of disturbance scenarios. The FIA program maintains a plot network across the country consisting of one randomly located plot per approximately 6000 acres (2428 hectares). The tree list from each of the FIA plots with at least one forest land condition on NFS land (within the NFS Region) is entered into FVS. For each scenario, a generalized C storage model is developed by combining results of simulations with similar starting tree lists. Each group of plots is subjected to a range of simulated disturbances to develop C storage models applicable to the gamut of observed disturbance patterns. Uncertainty measures from the fitting process are stored for later uncertainty analysis, as described more fully by Raymond et al. (2015).

ForCaMF's software simply applies regionally averaged C dynamics described on the right side of Figure 3 to the remotely sensed vegetation and disturbance history information summarized on the figure's left side. When disturbance affects a simulation unit (as indicated by the disturbance map), it is moved from an FVS-derived "undisturbed" carbon accumulation function to the appropriate post-disturbance function. If maps show the simulation unit to be disturbed again, it is moved to the new post-disturbance carbon accumulation function at the appropriate time (Healey et al., 2014). In calculating the impact of a particular disturbance process (D_F) from 1990 to 2011, the software effectively erases all disturbance flags to calculate potential C stocks under an undisturbed scenario (*N*) at each date, and then identifies the projected difference in C storage when just one of the mapped disturbance processes (e.g. fire, harvest, insects, disease) is added back in. This difference can be displayed for each year in the time series and for each type of disturbance. This timeline of impact allows quantitative comparison of the effect of each type of disturbance, particularly as events such as large fire years or emerging insect problems change overall C storage patterns.

5.1.2 Uncertainty

There are several potential sources of uncertainty in the ForCaMF workflow described above, including: mapped starting conditions (initial C storage and forest type); modeled disturbance magnitude; and modeled C accumulation model, as derived from FIA and FVS. These error sources are highlighted in red in Figure 3. Maps of disturbance year and type are not considered to be a significant source of error; the manual methods used to develop these maps in consultation with independent error records mimics methods used to develop "truth" data in other studies involving disturbance maps created with more automated methods (e.g. Cohen et al. 2010, Thomas et al. 2011, Schroeder et al.2014).

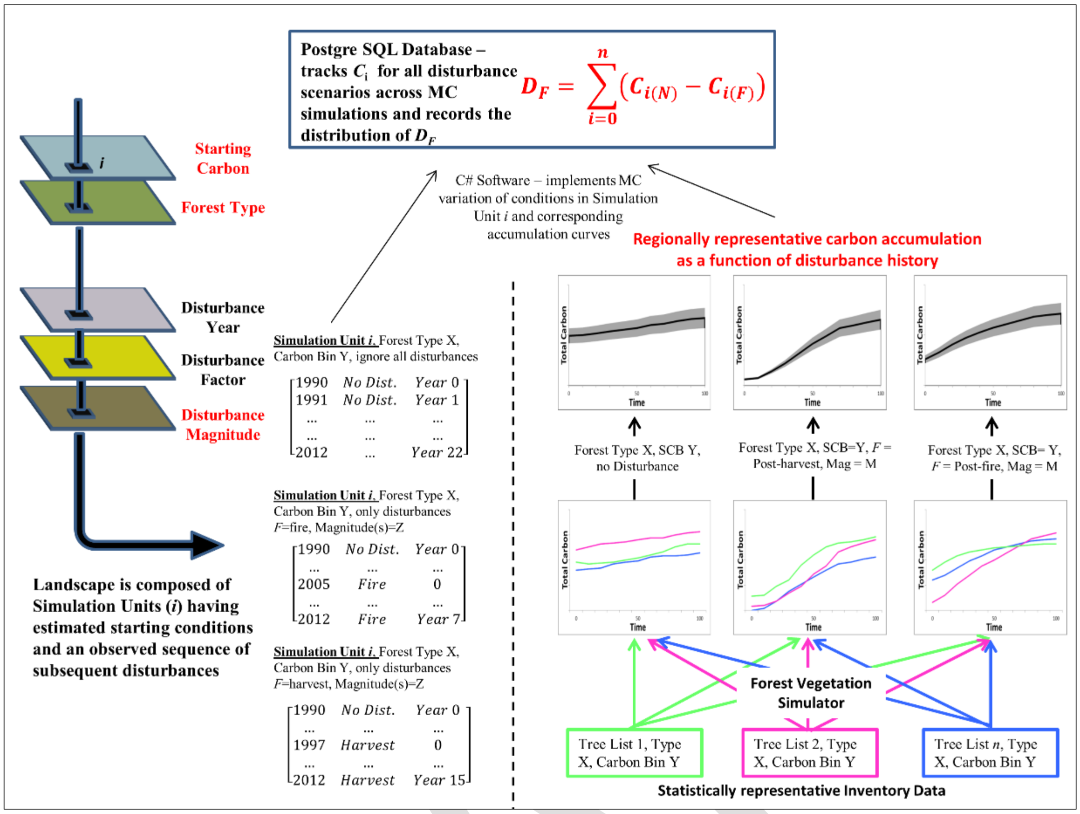

Figure 3. Flowchart of how ForCaMF calculates the impact of each type of disturbance. Carbon storage associated with mapped forest conditions and disturbances is determined by applying FIA-based regionally generalized carbon dynamics derived from the combination of FIA data and FVS.

The complexity and interaction of ForCaMF's potential error sources precludes solving for error using an analytical approach. Instead, a so-called "Monte Carlo" approach is used, where randomly selected alternative values for each input are substituted into the calculation of D_F over a large number of error simulations. The variance of D_F in response to simulation of possible error patterns produces an empirical estimate of the system's integrated uncertainty. Healey et al. (2014) described an innovative method of carrying out the Monte Carlo method with mapped inputs such as those used here. This process, called "Probability Density Function (PDF) Weaving," uses FIA data to calibrate and constrain error simulations related to mapped forest type and starting-condition maps as well as maps of disturbance magnitude As a result, ForCaMF analyses are aligned with FIA estimates of historical C storage, distribution of forest type, and forest cover change.

In addition to uncertainty in input map products, ForCaMF also simulates uncertainty associated with each of disturbance-specific, stand-level C scenarios (right side of Figure 3) that ForCaMF links to mapped stand dynamics (left side). Error functions are obtained from fitting each scenario via a process called quantile regression, as mentioned above and described by Raymond et al. (2015). These models are used to calibrate how C storage patterns are allowed to vary in the ForCaMF Monte Carlo process. The net result of these error simulation processes is that an empirical 95% confidence interval can be associated with estimates of DF for each year.

5.2 Integrated Terrestrial Ecosystem Carbon Model

5.2.1 Methodology

The Integrated Terrestrial Ecosystem Carbon (InTEC) model builds upon both CCT and ForCaMF in that it gives a full attribution of both natural and anthropogenic causes of observed forest C changes (Chen et al. 2000, 2000a, 2000b, Ju et al. 2007). InTEC is a process-based biogeochemical model driven by monthly climate data, vegetation parameters, and forest disturbance information to estimate annual forest C and fluxes in C pools at regional and local scales (Figure 4). InTEC relies on empirical FIA datasets (USDA Forest Service 2016) containing variables such as stand age, dominance (or forest) type, and net growth, resulting in a hybrid approach which combines a process-based biogeochemical model as well as empirical models that are comparable to the results from CCT and ForCaMF. Specifically the FIA-obtained stand age, dominance (or forest) types, and net primary productivity (NPP)-stand age relationships determine when stands were initially disturbed and depending on dominance type, how the productivity changes with age overtime.

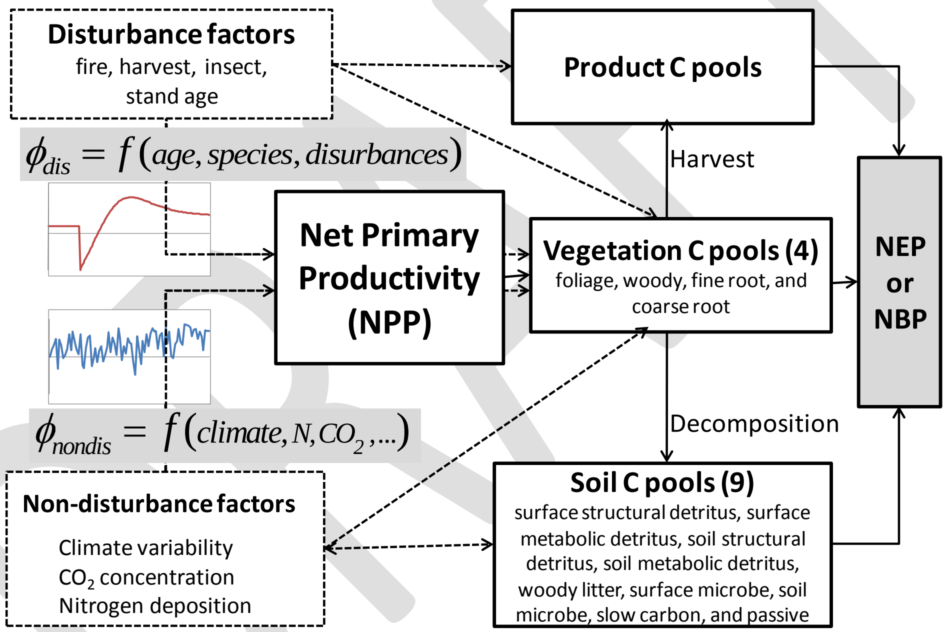

Figure 4. Conceptual scheme of the C cycle in the Integrated Terrestrial Carbon Cycle Model (InTEC). Solid arrows indicate C flow and dashed arrows indicate influences. $\phi_{dis}(i)$: disturbance function; $\phi_{nondis}(i)$: non-disturbance function; NEP: net ecosystem productivity; NBP: net biome productivity. NPP is the net production of organic matter by plants which is equal to the difference between the total amount of carbon fixed in photosynthesis (gross primary productivity) and carbon losses from respiration of plants (autotrophic respiration). NEP is equal to the sum of NPP and the C loss to the atmosphere via heterotrophic respiration. NBP is equal to the sum of NEP and C fluxes associated with non-respiratory losses due to disturbances such as combustion from fire or export to external pools following harvest. If no disturbances occurred in a given year, NBP is equal to NEP (Zhang et al. 2012).

The carbon dynamics of a forest region are a function of multiple factors including disturbance, stand age, climate, and atmospheric compositions (Chen et al. 2000). These are grouped into disturbance and non-disturbance factors. Disturbance factors include primarily fire, harvest, insects, and forest stand age or time since stand-replacing disturbance, which can include disturbances that are not specifically identified such as windstorms or diseases. Non-disturbance factors include climate (temperature and precipitation), atmospheric carbon dioxide (CO_2) concentration, and nitrogen (N) deposition. Forest stand age which indicates the time since disturbance influences the rate and accumulation of regrowth after disturbance. Nitrogen deposition and atmospheric CO_2 concentrations influence photosynthesis, respiration, and other variables in the model that determine C production. The InTEC model integrates the effects of non-disturbance and disturbance factors since the initial modeling year (1900 in this study). The historical C dynamics are estimated progressively through a mechanistic aggregation of disturbance and non-disturbance factors, and the results at any point in time are the accumulated effects of all factors since the starting year (Chen et al. 2003).

The InTEC model is run pixel-by-pixel, with a 90-m pixel size, in each individual national forest and summary results are presented by summing or averaging all pixels in a forest, depending on the measure being reported. Carbon pools include: aboveground live (wood and foliage), belowground live (coarse roots), forest floor (fine roots, surface structural & surface metabolic detritus), dead wood (standing & down dead, foliage, and coarse roots), and soil (soil structural & soil metabolic detritus, soil microbes, surface microbes, slow organic matter, and passive organic matter).

Disturbance, regrowth, and aging effects:

Disturbances are explicitly considered as processes that release C into the atmosphere, modify the terrestrial C balance, initiate regrowth, and subsequently transfer carbon from one pool to another (e.g. live trees to standing dead) in the disturbance year and thereafter. For the period 1990-2011, Landsat-obtained disturbance maps were developed, also for use in ForCaMF (Healey et al. 2014), to determine the year, location, type (fire, harvest, insects), and magnitude of disturbance events. For the earlier period without known disturbance dates, stand age maps were obtained from forest inventory data to act as proxies for the timing of the last major disturbance. Each pre-1990 disturbance is considered to be a stand replacing fire as it is difficult to differentiate by disturbance type from stand age alone and any disturbance that reset the stand age to zero would have been stand replacing—most likely a high-severity fire or clear cut harvest. The type and magnitude of each disturbance determine the amount of carbon released directly to the atmosphere as well as the transfer of carbon from live carbon pools to dead carbon pools as a result of mortality, and the regrowth trajectory.

For instance, if a fire has a mortality rate of 100%, a portion of the biomass C is immediately released to the atmosphere via combustion, the entire stand dies and C is transferred from the live to the dead pool, stand age becomes zero, and the stand regrows the next year following the forest dominance type specific NPP-stand age relationships. If a fire has a mortality rate of 50%, a portion of the biomass C is immediately released to the atmosphere via combustion, a portion (50%) of the live trees die, transferring C to the dead C pools, but the stand age remains the same, and the forest continues to grow following the NPP-stand age relationship.

For harvests, the C in the harvested wood is transferred to the harvested wood C pool, thus leaving the forest ecosystem. Wood that is not removed from the forest during harvest such as branches and roots is transferred to the appropriate ecosystem C pool such a woody debris. The removed C may be stored in the harvested wood products (HWP) pools for several decades. Refer to the Region 1 Carbon Assessment and Stockmann et al. 2014 for a detailed analysis of harvested wood product pools.

NPP-stand age relationships vary regionally, by forest types, and environmental conditions (He et al. 2012, Zhang et al. 2012). For forests in the U.S., NPP, which is the net production of biomass, typically increases rapidly at a young age, reaches a maximum in middle-ages at about the time the canopy closes, and then gradually declines and stabilizes with older ages. Consequently, middle-aged forests have a greater capacity to uptake C than young and old forests. In InTEC, the aging effects reflect these changing rates of carbon sequestration with stand age. After a disturbance, C changes may initially be negative (C source), but later become positive (C sink) and reach a peak as vegetation regrows and the decomposition declines (Pregitzer and Euskirchen 2004). Depending on a forest's stand age or the number of years since the last disturbance, the disturbance/aging effects on changing C stocks can be positive (causing a C sink) or negative (promoting a C source).

Non-disturbance effects:

Both long-term climatic trends and inter-annual climatic variability can impact forest C dynamics by affecting growth, productivity, and decomposition. Anthropogenic climate change has led to increases in average temperatures in most regions across the U.S. since 1900, as well as regional shifts in precipitation where some regions have become drier and others wetter (Walsh et al. 2014). In some regions, warmer temperatures can cause moisture stress and more rapid decomposition of surface and soil C (Ju et al. 2007), thus increasing C emissions. In high latitude or altitude locations, warmer temperatures can enhance tree growth (Way and Oren 2010). Drought conditions can reduce tree growth both during the drought and up to several years after, in turn making forests less able to act as C sinks (Anderegg et al. 2015). On the other hand, increased precipitation and humidity can enhance tree growth and C uptake (Nemani et al. 2002, Dale et al. 2001).

Like climate, atmospheric composition is known to impact plant growth and C dynamics (e.g. Law 2013, Pan et al. 2009, Hyvönen et al. 2007). Atmospheric CO_2 levels have increased steadily from 280 ppm in 1901 to 390 ppm 2010 (Keeling et al. 2009) due to human activities and industrialization. Elevated atmospheric CO_2 concentrations act as a fertilizer, stimulating photosynthesis and biomass production (Keenan et al. 2013). Similarly, the increased N deposition due to human activities can stimulate C sequestration in forests, through increased production of biomass, surface litter, and soil organic matter.

Simulation scenarios:

To model the effects of individual and combined disturbance and non-disturbance factors, a series of simulation scenarios were developed (Zhang et al. 2012, 2015). Typically, six overall scenarios are simulated by InTEC: 1) All factors including all disturbance/aging and non-disturbance effects, 2) Disturbance/aging effects only, 3) Combined non-disturbance effects only, 4) Climate effects only, 5) CO_2 effects only, and 6) N deposition effects only.

5.2.2 Uncertainty

Quantifying model uncertainty using a Monte-Carlo approach and multiple simulations is impractical with InTEC because of the time it takes to perform model runs given the numerous forests, high resolution datasets, long temporal scales, and multiple simulation scenarios analyzed. The uncertainty and validation of the InTEC model for analyses across the contiguous U.S. were studied in Zhang et al. 2012 and Zhang et al. 2015. However uncertainties also depend on the quality and quantity of data available for each forest. It is important to consider that InTEC is highly calibrated to FIA data and satellite imagery observations of disturbance and productivity and uses disturbance estimates and age maps, so that the previously assessed uncertainties in these datasets are propagated into the InTEC model results. Given the lack of stand age data in the early part of the 20^{th} century, modelled results are more uncertain for that period (Zhang et al. 2015), thus results prior to 1950 are omitted.

For additional information regarding the InTEC model including calibration, parameterization, and model inputs, see Zhang et al. 2012, and 2015.

6.0 Regional Results

6.1 Effects of disturbance and management activities (ForCaMF) regional summary

The primary purpose of ForCaMF is to understand the relative impacts of different kinds of disturbances in the last 2 decades on current stocks. Baseline rates of disturbance are critical to both estimating and understanding these impacts. Mapped rates of fire, harvest, and insect activity for the Northern Region are displayed in Figure 5. Recall that the disturbance maps used in this project were manually edited to agree with spatial records of management, fire, and insects, as well as with high- and medium-resolution imagery. Regional disturbance patterns are marked with declining (and low) harvest levels, periodic large fire years (including 2000, 2004, and 2007), and a recent increase in insect activity.

In addition to these processes, root disease is known to substantially affect stand dynamics in parts of the region (Byler et al. 1990). Much of the impact of root disease is manifested in reduced growth rates and suppression of regeneration, which can be difficult to detect using remote sensing. However, FIA maintains a regional root disease severity variable (over 9 classes) for an area covering 6 of the Region's forests (Lolo, Bitterroot, Nez Perce Clearwater, Flathead, Idaho Panhandle, Kootenai). A total of 29% of the sub-plots in those forests had detectable signs of root disease in the last available measurement. This assessment assumed this rate of infection to be constant throughout the observation period, although infection is dynamic and generally grows over time. While root disease can remain on a site for decades and infection in the region was well established before 1990 (Byler et al. 1990), this likely resulted in some degree of over-estimation of disease prevalence during the early parts of the study period. On the other hand, no root disease was accounted for in forests not covered by the Disease Severity variable, certainly causing some omission of disease effects.

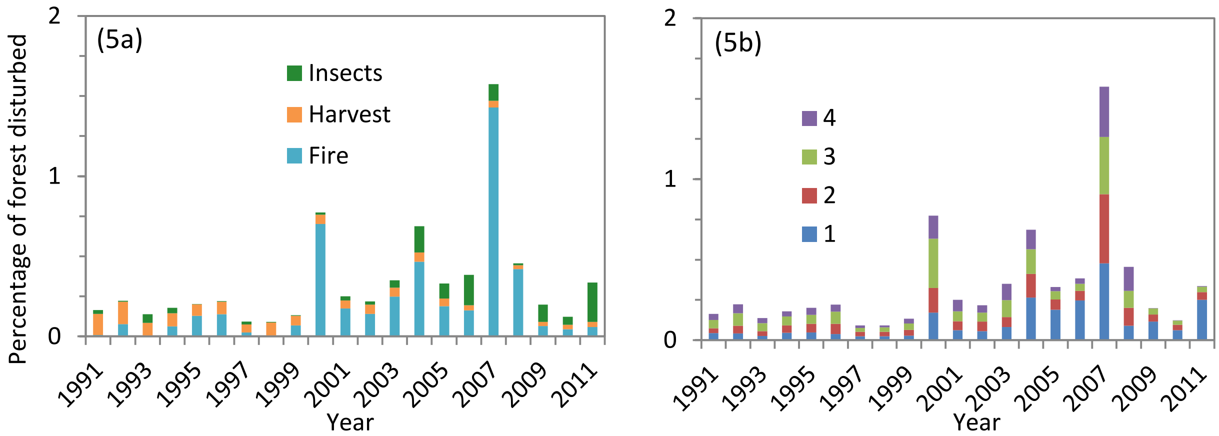

Figure 5. Regional rates of disturbance mapped using visual interpretation of several independent datasets and summarized as the percentage of the forested area disturbed from 1991-2011 by: (a) Disturbance types including fire, harvests, and insects; and b) magnitude classes, characterized by percentage change in canopy cover (CC) and categorized as follows, 1) 0-25% CC, 2) 25-50% CC, 3) 50-75% CC, and 4) 75-100% CC.

The estimated impact of disturbance as assessed through ForCaMF is displayed in Figure 6. It is critical to understand that the impact of disturbance (D_F, as defined in Eq. 1) is expressed in relation to the amount of C that would have been stored in the absence of the particular disturbance process. This means that the impact of a disturbance is felt beyond the year it happens. If fires only show up in 2006, for example, the line in Figure 6 for fire will only start to diverge from zero in that year (subject to some Monte Carlo error simulation noise) and the fire line may continue to diverge because, even if the stands are not C sources, their net storage in the years after the fire is likely to be less than if the fire had not occurred. Thus, Figure 6 reflects the long-term impact of disturbance on the forest's ability to store C.

The long-term impact is especially evident in the estimated effects of harvest. Effects continue to increase, albeit very slowly (relative to C that would have been stored in the absence of harvest) even though harvest activity virtually ceased, region-wide, during the 1990s. It is important to reiterate that these patterns do not account for off-site storage of carbon in wood products. Few fires were detected during the early 1990s, so the line for fire starts near zero. However, following an increase in large fires that began around 2000, the impact of fire on carbon stocks greatly increased. Because of the residual effects just discussed, the effects of these fires will likely continue (and perhaps increase) through future decades both because carbon added through recovery may not equal C that would have been added through continued growth, and because decaying material killed by the fire will mitigate C added through recovery.

Recent increases in the area affected by insect activity (Figure 6) are translated into recent increases in the impact of insects on C storage (Figure 7). Root disease was a dominant disturbance factor because it affects a large portion of the Region, and because its steady suppression of growth and regeneration represent a chronic limitation on affected stands to add C. One caveat must be stated related to the confidence intervals depicted in Figure 7. The true unit of analysis for ForCaMF was the national forest; rates of simulated error were constrained by FIA estimates at that level. The regional aggregation used a secondary Monte Carlo analysis based upon the uncertainty of each individual forest result, and it assumed that the errors in one forest were independent of errors in other forests.

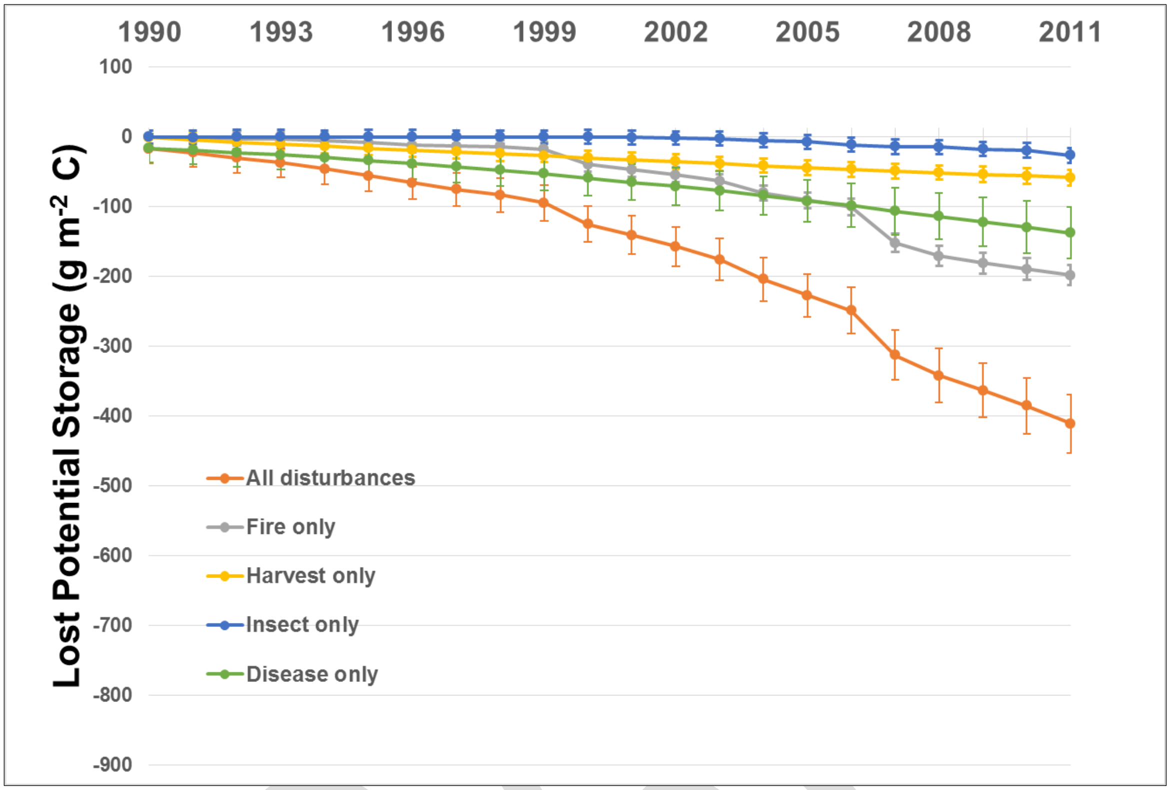

Figure 6. Lost potential storage of carbon as a result of fire, insect, and harvest on each national forest in the Northern Region for the period 1990 – 2011. Specifically, the difference in storage for each year is shown between a "no-disturbance" scenario and a scenario which includes only observed amounts of the specified type of disturbance. Error bars represent 95% confidence intervals. One hundred grams per square meter equals one metric tonne (or Megagram) per hectare.

This assumption is likely to over-state certainty at the Regional level; if initial biomass estimates in one forest are high, for example, the same estimates are also likely to be biased high in other regions. This caveat does not affect overall trends seen at the Regional level, nor does it affect confidence intervals assessmented at the national forest level. Overall effects of disturbances occurring in the region from 1990 to 2011, represented in terms of effect on 2011 storage, are displayed in the pie chart in Figure 6. Fire is clearly the dominant process, but root disease also strongly affects carbon storage in the region. The importance of insect activity, while currently relatively small, was virtually undetectable through the 1990s. Its growth parallels recent increases in the area affected (Figure 7).

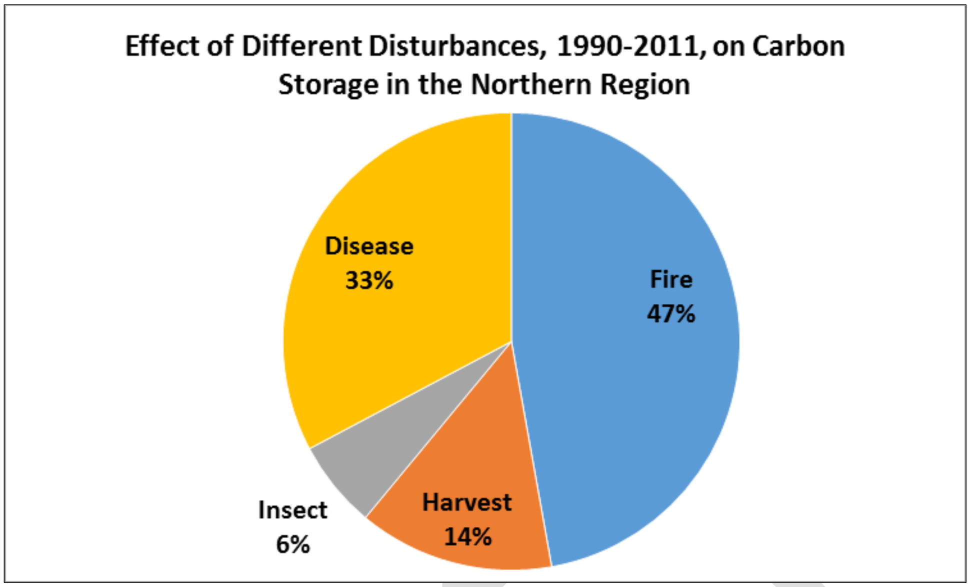

Figure 7. The effect of fire, insect, disease and harvest on carbon storage in each national forest of the Northern Region for the period 1990 – 2011.

6.2 Effects of disturbance, management, and environmental factors (InTEC) regional summary

This section provides a regional summary of the predicted (modeled) effects of land management, natural disturbances, and environmental factors on forest C dynamics through a series of figures (Figs. 8 – 11) generated by InTEC simulations for individual forests and summing results across all 11 National Forests in the Northern Region. These regional-scale outputs were generated from only the National Forest-specific datasets, thus these outputs do not represent lands within the region that are outside of the National Forest boundaries. Appendix C shows the effects of disturbance and non-disturbance factors on forest C dynamics within each National Forest as modeled by InTEC using this same series of figures.

According to the historical data and model results, forest C trends across the National Forests in the Northern Region have been strongly influenced by the history of land use and policies as well as climate change and natural disturbances. Despite variation among National Forests, the region-wide stand age distribution in 2010 shows that the majority of the stands in the Northern Region are older (>80 years old) with a distinctive pulse of stands which established between roughly 80-110 years ago or from 1900 to 1930 (Figure 8). After 1930 the rate of establishment dramatically declined. This early 1900s pulse in stand establishment may be a result of regeneration after the last major fires before fire-suppression, such as those in 1889 or 1910, or after timber harvests which intensified in the early 1900s (Baker et al. 1993). Fire suppression, which began in the early 1900s would have allowed more of these young, regenerating stands to survive and continue re-growing rather than being disturbed at a more typical historical rate of fires (Pyne 1982). Depending on the forest dominance type, which is mostly Douglas-fir and Subalpine fir, stands comprising this pulse of establishment would have reached maximum productivity between 30-60 years of age (Figure 9), or throughout the mid-to-late 20th century. Forests in the Northern Region show another pulse of young stands (<20 years old) (Figure 8) which established between 1990 and 2010, suggestive of regeneration after recent large and often severe disturbances—mostly fires (Figure 5, Section 6.1).

Climate has on average gotten warmer and slightly drier in this region (Figure 10 a-b). The warmer temperatures and drier climate can increase soil respiration and evaporative demands as well as water stress leading to declines in net ecosystem productivity and increased C released to the atmosphere. As climate continues to change, this region is expected to get even warmer and potentially drier into the future. Both atmospheric CO_2 concentrations and nitrogen (N) deposition (Figure 10c) have increased over the past few decades as a result of human activities.

The C stock changes across the National Forests in the Northern Region show that together the forests have generally experienced a switch from a C sink to a C source (Figures. 11 a-c) and a decline in accumulated C (Figure 11d). Disturbance and aging effects have been mostly responsible for declining C stocks (Figure 11b), which correspond to disturbances that shaped forest age structures (Figure 8), the NPP-stand age relationships (Figure 9), and increasing disturbances in recent years (Figure 5, Section 6.1). From 1950 to around 1980, the forests were mostly a C sink due to positive disturbance/aging effects, as the early 1900s pulse of stands was middle-aged and therefore growing at peak productivity. As these forests further aged, productivity declined, causing the rate of C accumulation to decline (Figure 11d). Meanwhile the effects of disturbance were increasing to the point where C emissions due to decomposition/decay and disturbances exceeded C gains, and as a result the forests became a C source (Figure 11b, c). This decline was coupled with lower rates of stand establishment in the mid-1900s.

The ForCaMF model results indicate that disease caused a significant loss of potential C storage over the past two decades (Figure 6). While the InTEC model did not explicitly consider the effects of disease disturbances, if disease caused stand replacing mortality it would be reflected in the current age structure, thus included in the InTEC model. However, any lower severity disease disturbances were not directly modeled by InTEC. Therefore, it is likely that disturbance/aging caused an even greater C source in recent decades than the InTEC results suggest.

Although recent disturbances initially caused increases in C emissions during the year of the disturbance events (Figure 11e), they also promoted regrowth and recovery as evidenced by the recent pulse of stands aged 0-20 years (Figure 8). As these young stands recover and reach middle-age in the coming decades, they will be growing at higher productivity (Figure 9), thus forests have the potential to accumulate more C and become C sinks again.

Climate variability and the recent warming trend has had a mostly negative effect on C stocks, also contributing to the switch to a C source (Figure 11a) and loss of C (Figure 11d). Future warming may result in an intensification of these already negative climatic effects. The increases in N deposition (Figure 10c) and atmospheric CO_2 concentrations have both had positive effects on changing C stocks and C accumulation across all forests in this region (Figure 11a, d). However the gains from CO_2 fertilization and N deposition were generally overshadowed by C losses due to negative disturbance/aging effects and climate effects (Figure 11d). Atmospheric CO_2 concentrations are expected to continue increasing for the foreseeable future, potentially counteracting the projected negative effects of climate.

Although a few National Forests in the Northern Region experienced a net gain of total forest C, most forests experienced a loss from 1950-2010 (Appendix C), resulting in a region-wide loss of approximately 74 Tg C of total ecosystem carbon, including soil carbon (Figure 11d).

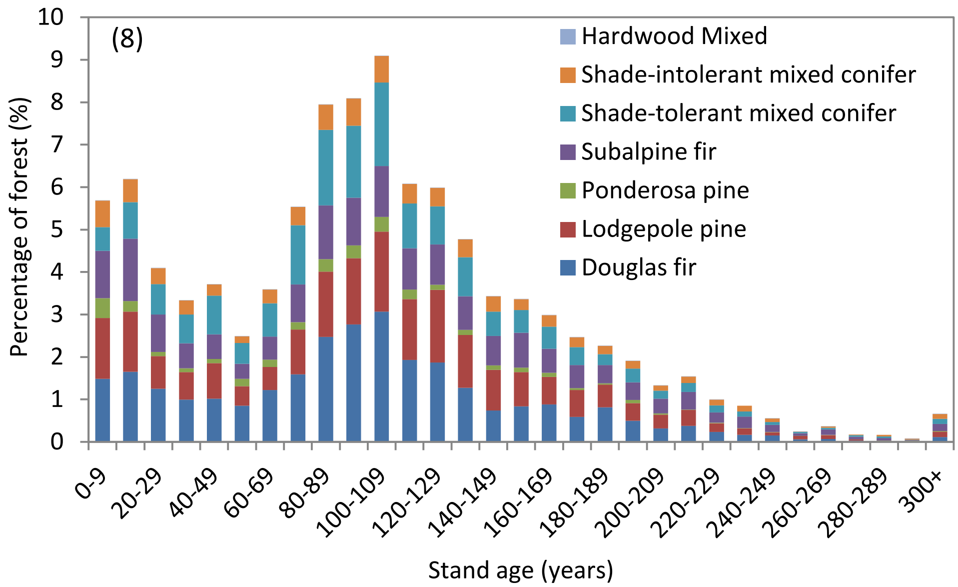

Figure 8. Age class distribution in 2010 displaying the percentage of forest land of each forest dominance type in 10-year age classes summed across all National Forests in the Northern Region. Dominance types are symbolized by stacked, colored bars.

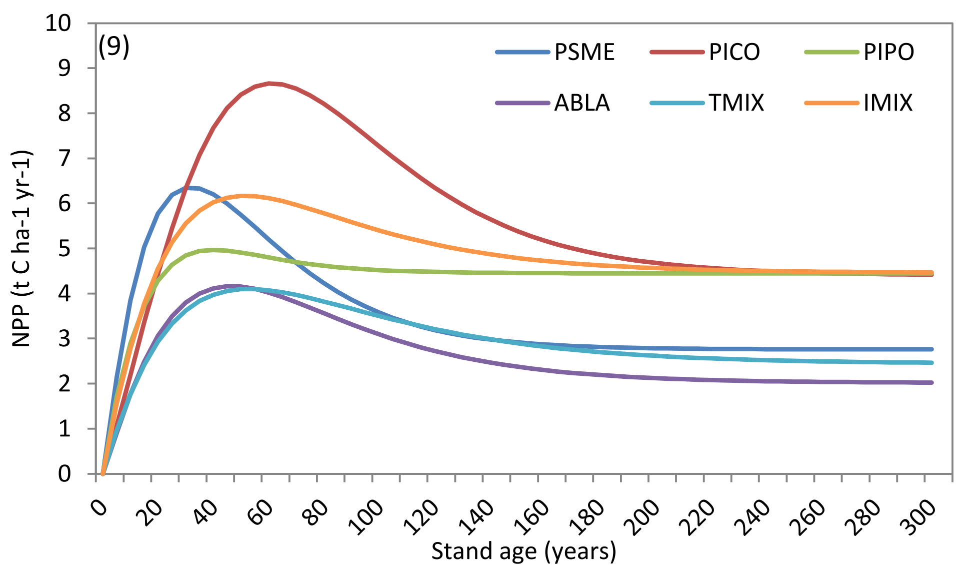

Figure 9. Relationship between net primary productivity (NPP) and stand age for each forest dominance type averaged across all National Forests in the Northern Region. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed

conifer (TMIX), and shade-intolerant mixed conifer (IMIX). Note: Due to an inadequate sample of hardwood mixed (HMIX) plots to derive NPP-age curves, the IMIX curve was used for the HMIX stands.

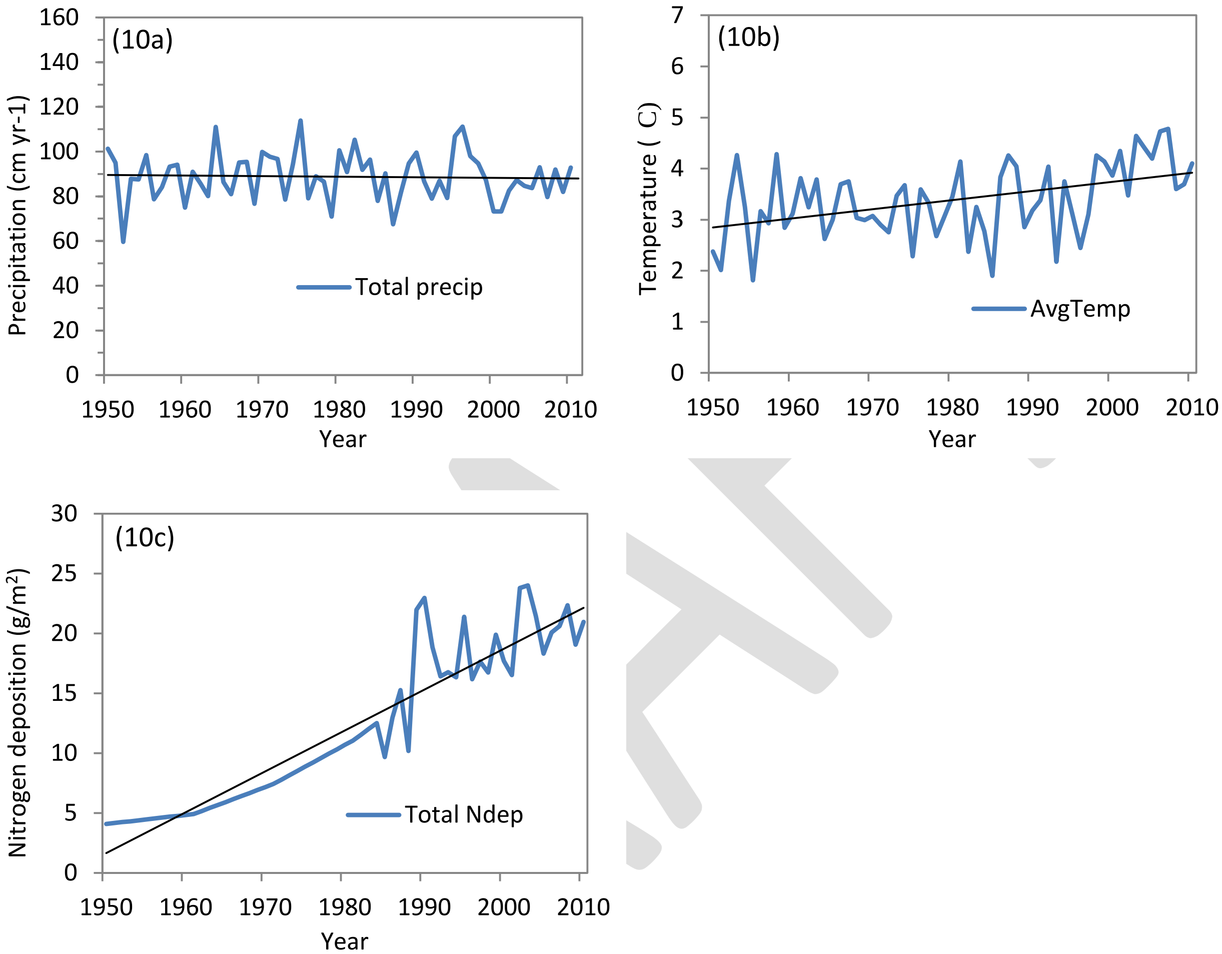

Figure 10. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010 averaged across all National Forests in the Northern Region. Linear trend lines shown in black.

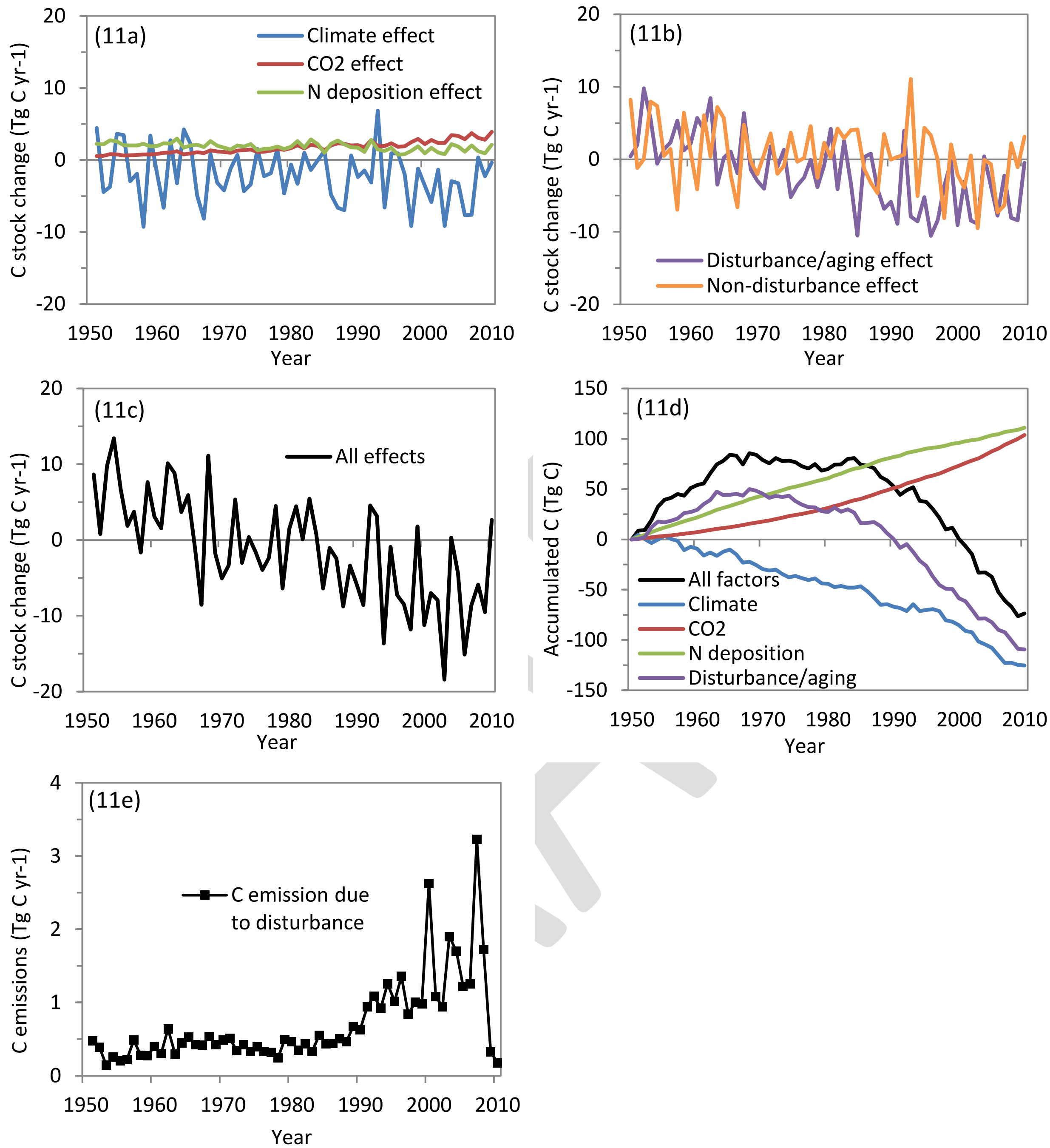

Figure 11. Estimated forest C changes and accumulations summed across the National Forests in the Northern Regions. Changes in C stocks are attributed to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance\aging factors including fire, harvest, insects, and regrowth and aging, and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects. (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950. (e) Direct C emissions to the atmosphere due to disturbance events only. Positive values in Figures 11a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

7.0 Interpretation of data and model results

NFS forest carbon assessments are based on a variety of data sets and several models, and although we have attempted to reach a high level of consistency, appropriate interpretation and use of the results should reflect inherent differences between data sets and models that cannot be fully reconciled. Generally, the FIA data represent the most accurate analysis of trends in carbon stocks as summarized by the CCT model; the effects of disturbances are best captured by ForCaMF; and the effects of environmental variables are reflected in the results from InTEC. However, despite the extensive use of FIA data by all 3 models (CCT, ForCaMF, and InTEC), results are not 100% compatible because ForCaMF and InTEC use additional data sets with different properties, the models include different C pools, and because of differences in timing of observations from the different data sources. The models themselves are also different. CCT and ForCaMF are empirical models whereas InTEC is a hybrid empirical/process model. These different approaches are necessary to provide a complete analysis of the main drivers of change. It is worth noting that a land manager may be faced with interpreting conflicting results from studies conducted by different parties; therefore, it is hoped that this section provides some guidance for dealing with this situation in the future.

The three models (CCT, ForCaMF, and InTEC) that were integrated for these forest C assessments use common data sources to enhance agreement between model results. For instance, all three models use FIA data as major inputs so that all results are well grounded in observations. FIA data is the primary data source of CCT, as the model calculates C stocks and stock changes from tree-level data from at least two inventories using allometric models (Woodall et al. 2011). ForCaMF also relies on FIA data to simulate forest C trajectories given different disturbance scenarios (Raymond et al. 2015). Lastly, InTEC is driven by stand age maps, dominance type maps, and NPP-age relationships, all in part obtained from FIA plot data.

Along with FIA datasets, ForCaMF and InTEC incorporate high-resolution Landsat-obtained disturbance data (Healey et al. 2014). Although FIA captures disturbance events, it may lack the temporal sensitivity to detect more recent disturbances. This is because FIA field observations are made on a cycle that may be as long as 10 years or even longer, and in some cases older observations are based on periodic inventories and newer observations are based on annual inventories of subsets of sample plots, so that the average vintage of the FIA data (particularly in the West) can be 5 or 10 years. The CCT model interpolates and extrapolates these observations to produce an annual time series since 1990, but if the extrapolation is from older data and there have been significant changes such as an increase in disturbances, the extrapolation represents trends that are no longer representative of what is occurring in the landscape. In contrast, ForCaMF and InTEC both use remote sensing observations as major inputs, and these observations reflect landscape changes as they occur.

FIA may also lack spatial resolution to detect smaller disturbances outside FIA plots, especially in areas where plot density is sparse. On the other hand, the Landsat satellite captures any recent disturbance greater than pixel resolution (30m) that alters forest canopies, even those occurring outside FIA plot locations. ForCaMF utilizes all identified disturbance types including fire, harvest, insects, disease, and abiotic disturbances (e.g., wind, ice). InTEC excludes disease and abiotic disturbances due to the complexity and uncertainty in including their effects in a process model. Also, except for Region 1 which has had significant disease impacts as indicated by ForCaMF, both diseases and abiotic disturbances affect a relatively small percentage of national forests across the U.S. as compared with other disturbance types.

Although InTEC and ForCaMF both evaluate the effects of disturbances and management on C stocks, there are several key differences between the models that make direct comparison of their results difficult. ForCaMF only models the effects of disturbance/management on non-soil carbon stocks, while InTEC not only includes soil carbon, but also extensively tracks the complex C cycling through several soil C pools (see Section 5.2, Figure 3). This is a significant difference as soil C is often one of the largest single C pools in forest ecosystems. Additionally, ForCaMF is primarily tracking potential lost C storage as a result of disturbances and management, while InTEC is mostly focused on C stock changes and accumulations due to both disturbance and non-disturbance factors. Therefore, while these models complement one another, direct comparisons between the two are limited.

Model results may also vary due to inherent differences in modelling approaches. For instance, CCT relies on allometric models of volume, species, and tree dimensions to convert tree measurements to biomass and to C (Woodall et al. 2011). ForCaMF is similar in that it also uses individual tree measurements and site characteristics within the Forest Vegetation Simulator (FVS) growth and yield model to simulate C stocks and trends. InTEC is fundamentally different as it is a hybrid empirical/process model which is driven by biogeochemical cycles such as photosynthesis, N mineralization, and nutrient dynamics (Zhang et al. 2012, 2015), thus does not rely only on biometrics. These distinctions in modeling techniques are likely to result in some discrepancies between forest C outputs from the three models.

Lastly, the area of forest land in each National Forest may differ by model. Both CCT and ForCaMF use the FIA definition of forest land as areas at least 36.6 m (120 feet) wide and 0.4 ha (1 acre) in size with at least 10 percent cover (or equivalent stocking) by live trees of any size, including land that formerly had such tree cover and that will be naturally or artificially regenerated (O'Connell et al. 2014). Thus the amount of forest land can change over survey years given deforestation or afforestation activities or administrative boundary changes. However, the changes in FIA sampling design, protocols, definitions in the late 1990s have been found to introduce discontinuity in attributes like total forest land area and consequently C estimates overtime (Woodall et al. 2011, Goeking 2015). InTEC uses a single dominance type map based in part on FIA data (Ruefenacht et al. 2008) and, where available, data sampled by the National Forest System (USDA Forest Service 2015b), thus the model assumes there is no change in area of forestland over the study period, in contrast to CCT and ForCaMF. While the extent of the effects of such modeling disparities on differences in forest C estimates has not been evaluated, it is important to consider that model results for individual forests may differ, sometimes considerably, for a variety of reasons.

8.0 Contacts

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10.0 Acknowledgements

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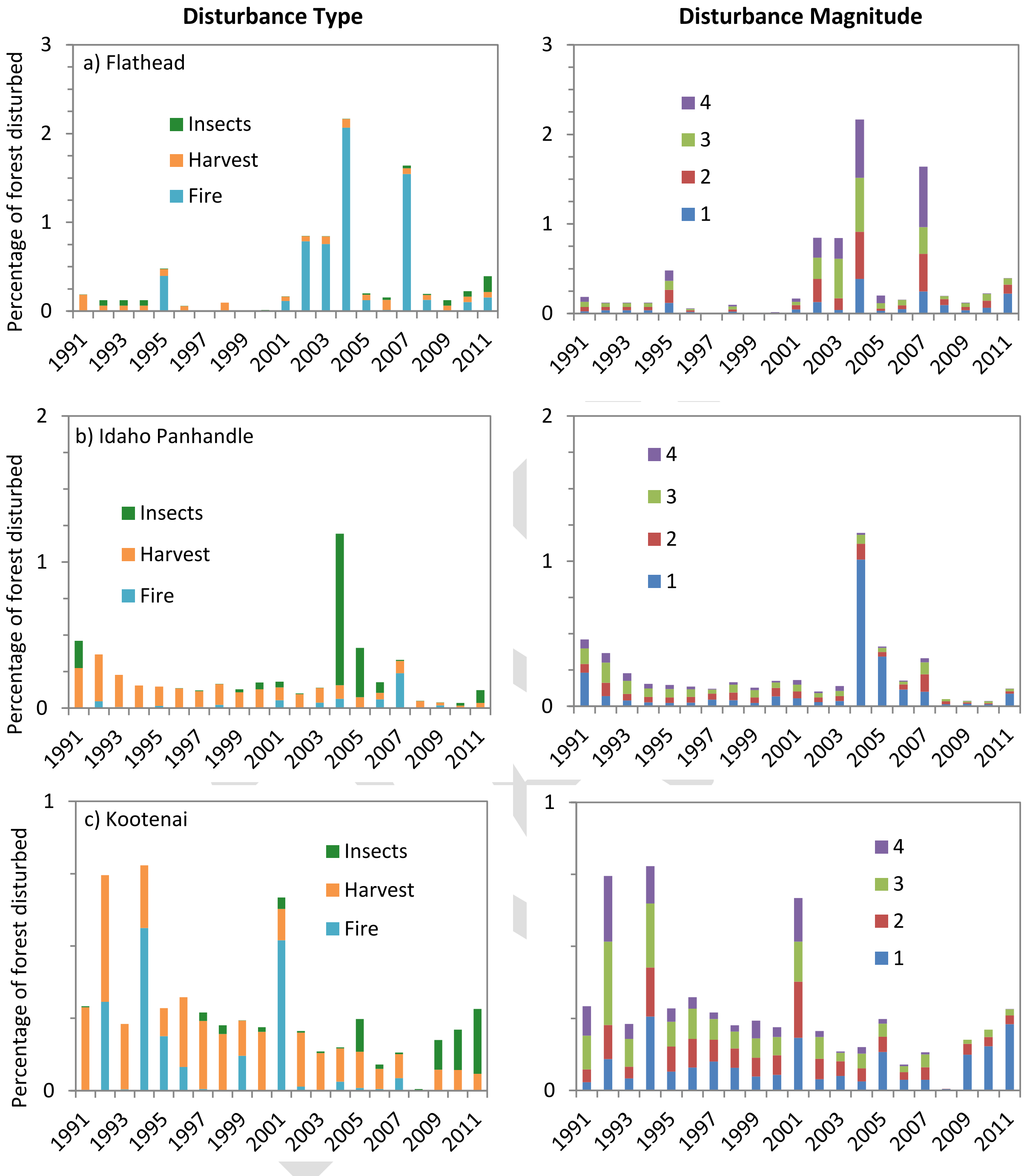
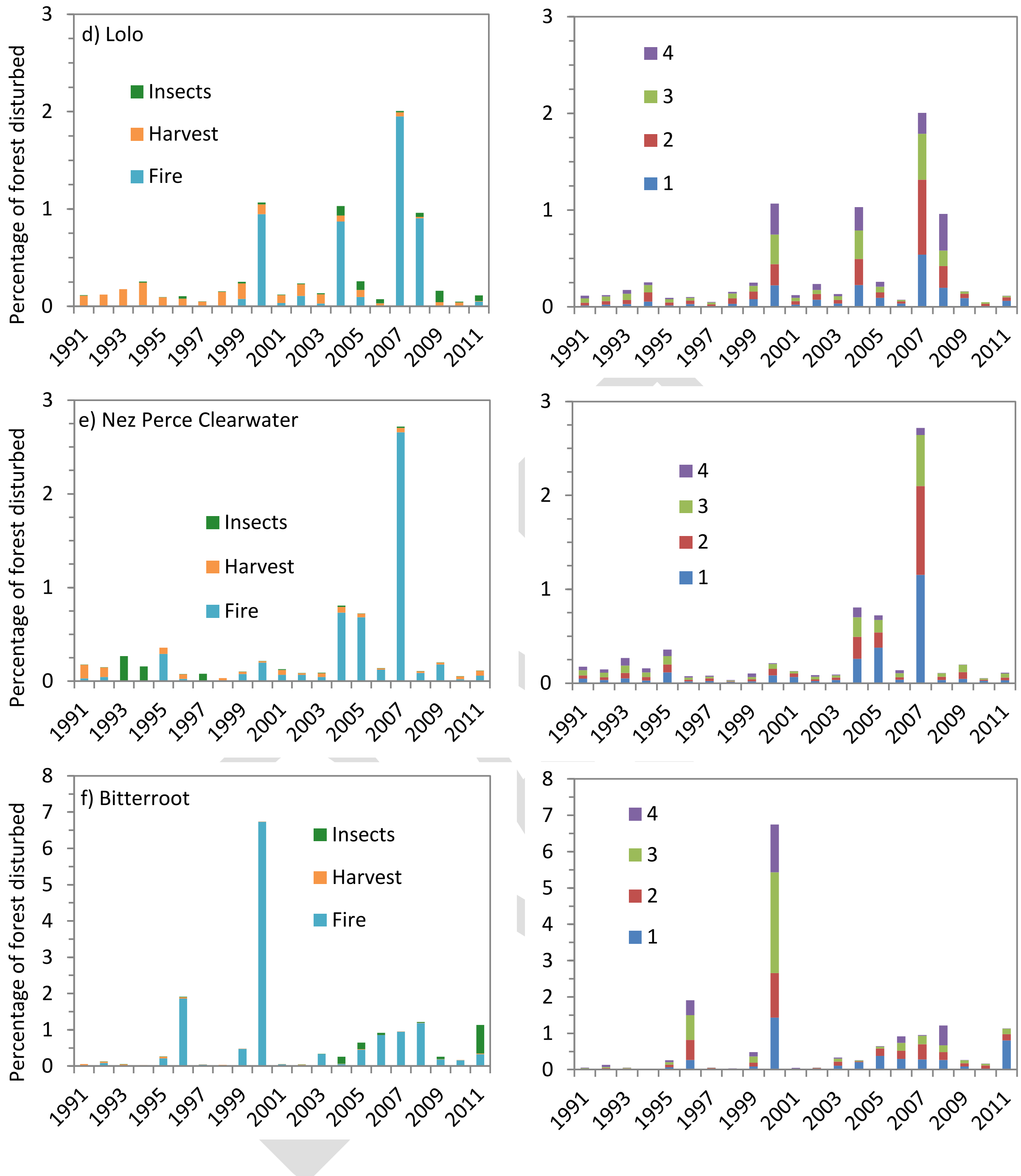
11.0 Appendix A: Effects of disturbance and management activities (ForCaMF) for individual National Forests in the Northern Region

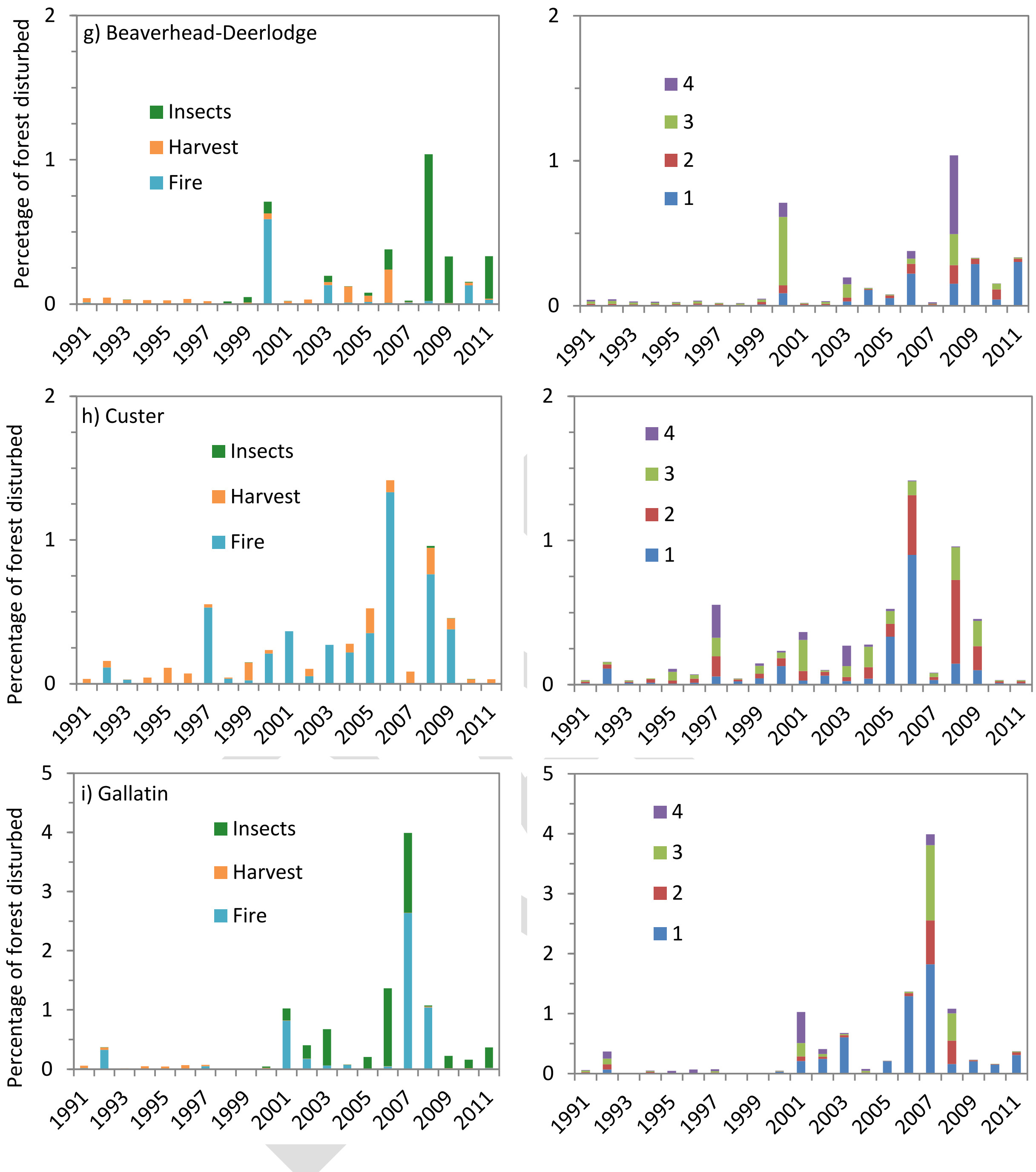
ForCaMF uses carbon dynamics derived from the combination of FIA plot data and FVS to interpret the consequences of recorded harvests and natural disturbances. This appendix contains ForCaMF results for each national forest in the Northern Region from 1990 to 2011. Disturbance records are summarized by type (fire, harvest, insects, disease) and by magnitude in Figure 1 a-k. In the Flathead National Forest (Figure 1a), for example, there were significant fire events affecting more than 1% of all forestland in 2002-2004 and 2007. Harvest in that forest affected approximately a quarter of a percent of forestland in the early 1990s and generally declined throughout the monitoring period. Mortality due to insects was picked up only in 2011. Not shown in Figure 1 is the rate of infection due to root disease, which was not mapped over time but was instead estimated from the FIA root disease severity variable.

The disturbance patterns depicted in Figure 1 a-k are clearly visible in the ForCaMF representation of carbon impact over time (Figure 2). In the Flathead, for example, the impact of fire significantly increased in the years corresponding to major fires. It must be emphasized that there is a residual effect for almost every disturbance because impact is being compared to what would happen to carbon storage if the stand had remained undisturbed. For fires, ForCaMF accounts for gradual decay of fire-killed material, so net carbon storage will likely continue to diverge from the undisturbed scenario for several years. This explains the fact that there is still an impact of harvest in the Flathead in 2011 despite low recent harvest rates; most stands harvested in the early 1990s have not yet reached the storage levels they would have attained if they had not been harvested.

Units in Figure 2 represent reduced carbon storage on a per square meter basis. Error bars around the impact of each type of disturbance represent 95% confidence intervals derived from 500 simulations of all recognized constituent uncertainties, as described earlier. Figure 3 summarizes the ForCaMF output shown in Figure Y: the pie chart represents the proportional importance of each type of disturbance as measured in 2011 (the last date in Figure 2). In the Flathead illustration, wildfire and root disease affected carbon storage from 1990 to 2011 much more than harvest and insect activity.


Disturbance Type
Disturbance Magnitude
Percentage of forest disturbed
a) Flathead
b) Idaho Panhandle
c) Kootenai
Insects
Harvest
Fire
4
3
2
1
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011


d) Lolo
Insects
Harvest
Fire
Percentage of forest disturbed
0
1
2
3
4
1991
1993
1995
1997
1999
2001
2003
2005
2007
2009
2011
e) Nez Perce Clearwater
f) Bitterroot
5
6
7
8


g) Beaverhead-Deerlodge
Percetage of forest disturbed
Insects
Harvest
Fire
4
3
2
1
h) Custer
Percentage of forest disturbed
i) Gallatin
1991 1993 1995 1997 1999 2001 2003 2005 2007 2009 2011

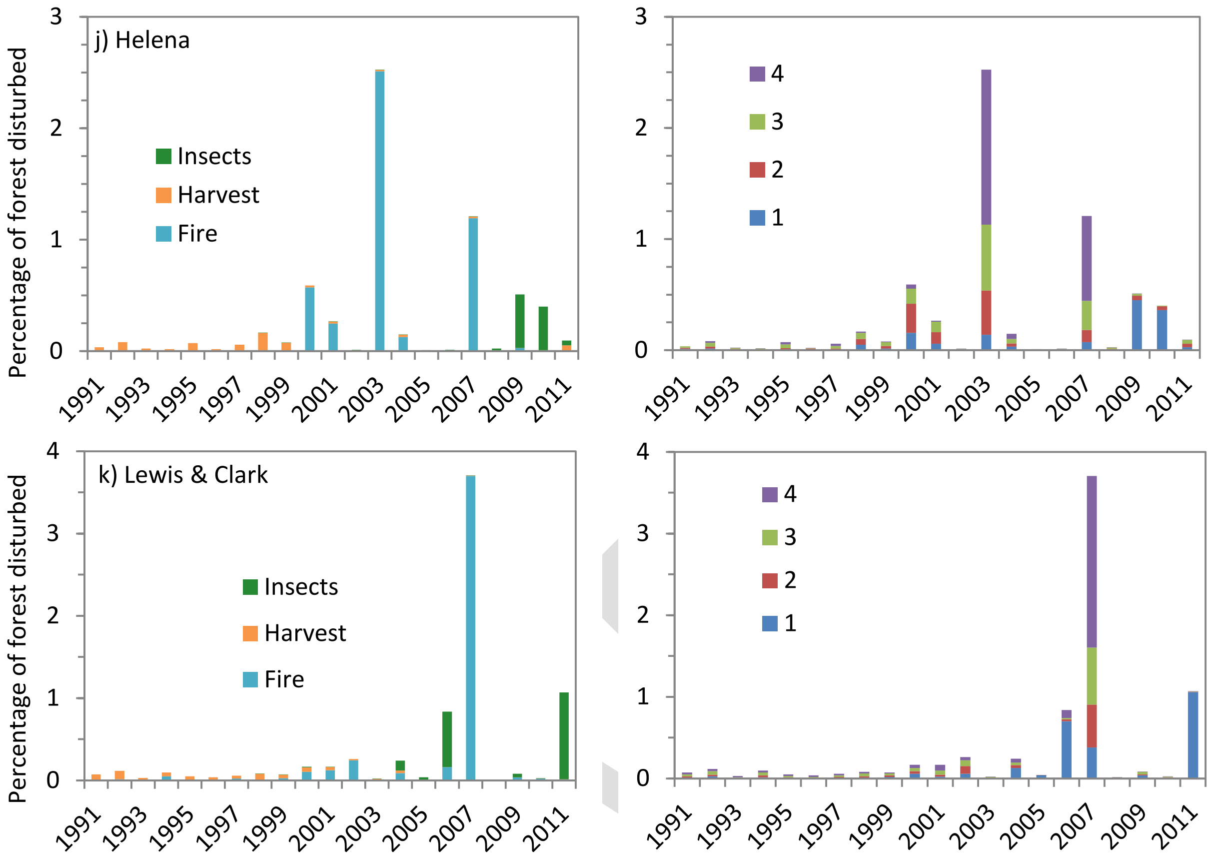
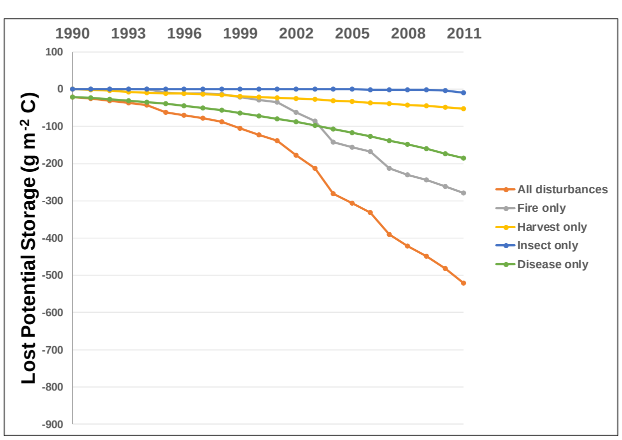
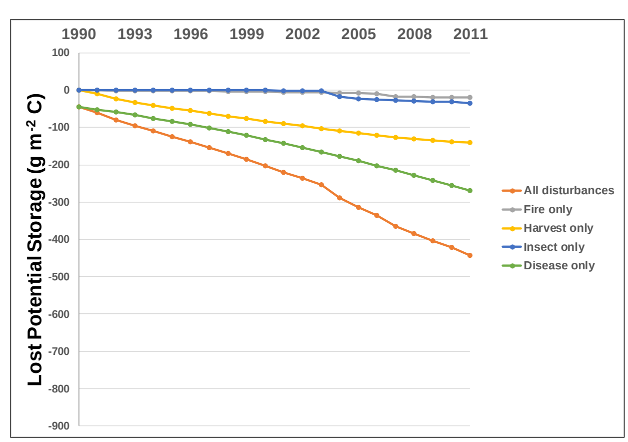


Figure 1. Percentage of the forested area disturbed from 1991-2011 by: (a) Disturbance types including fire, harvests, and insects; and b) magnitude classes, characterized by percentage change in canopy cover (CC) and categorized as follows, 1) 0-25% CC, 2) 25-50% CC, 3) 50-75% CC, and 4) 75-100% CC.

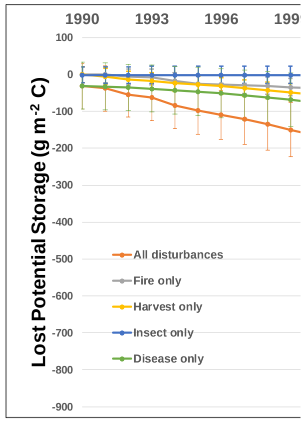
2a) Flathead National Forest



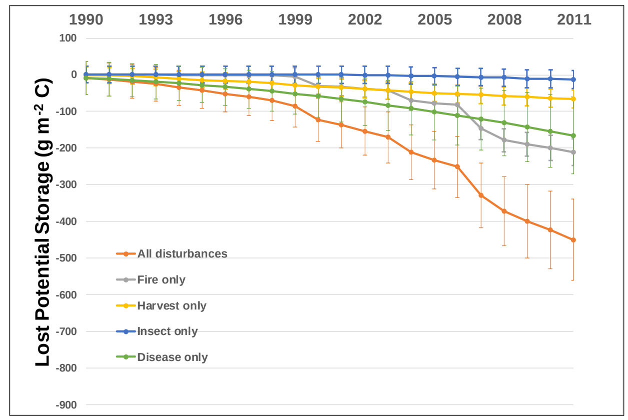
2b) Idaho-Panhandle National Forest



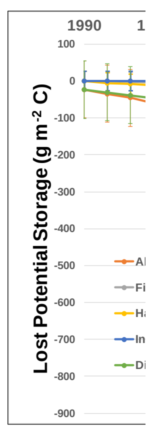
2c) Kootenai National Forest



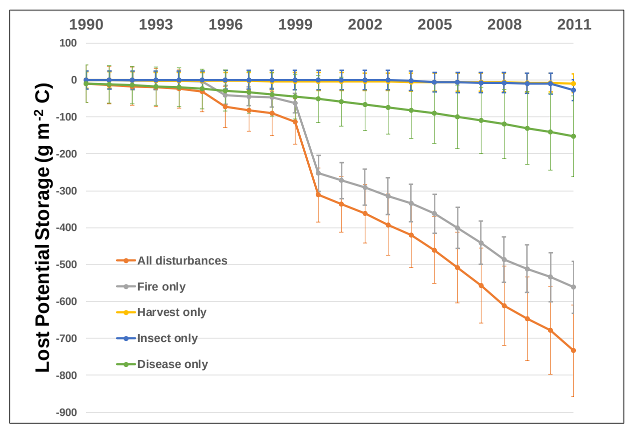
2d) Lolo National Forest



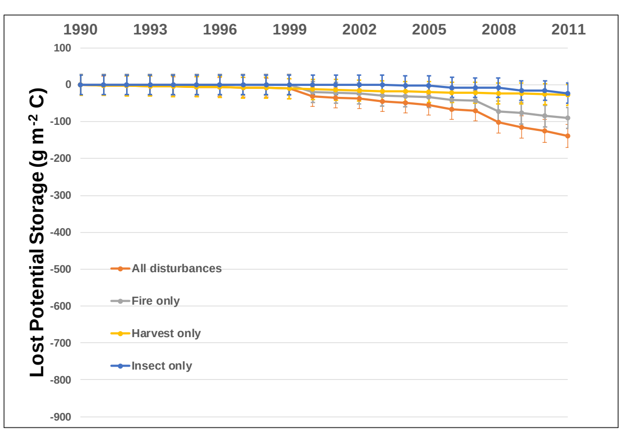
2e) Nez Perce-Clearwater National Forest



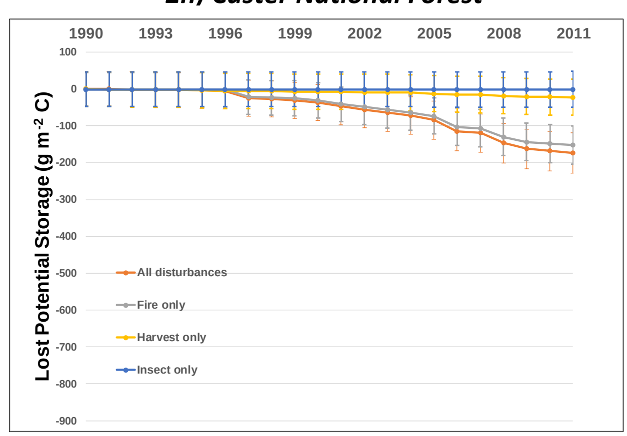
2f) Bitterroot National



2g) Beaverhead-Deerlodge National

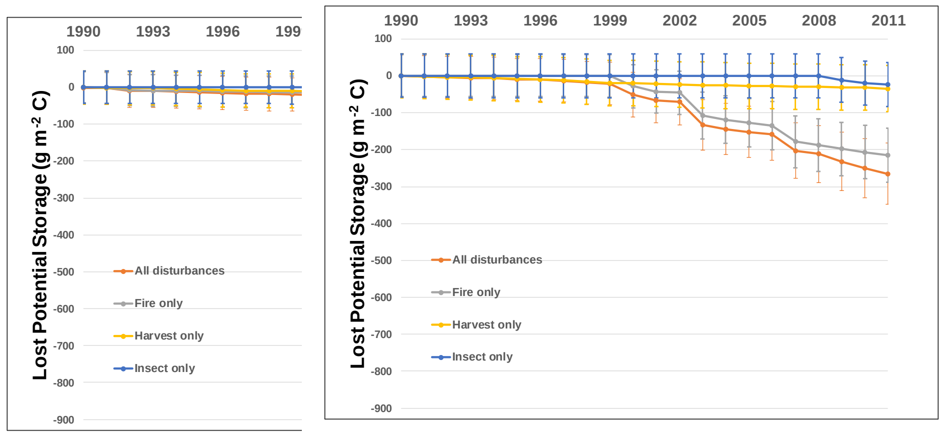


2h) Custer National Forest



2j) Helena National Forest

2i) Gallatin National Forest



2k) Lewis and Clark National Forest

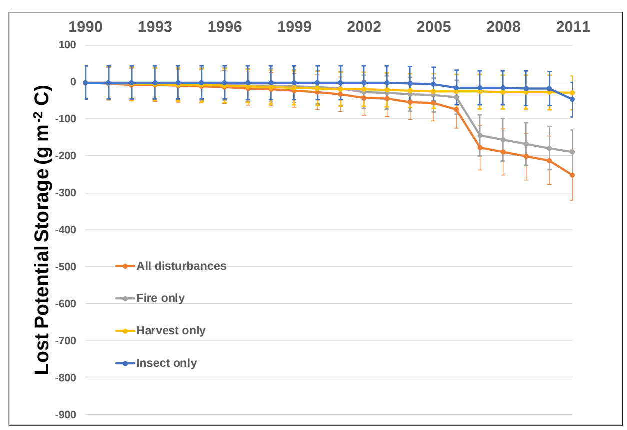
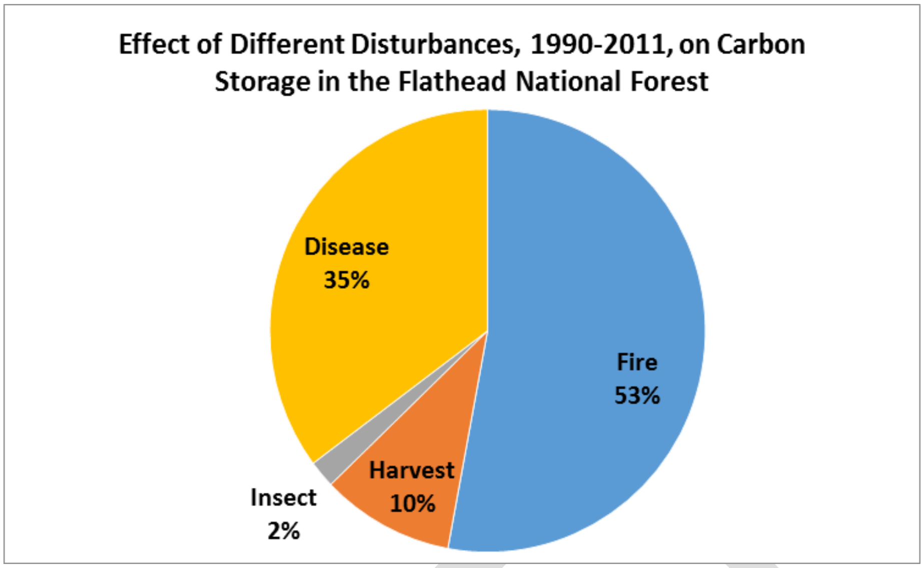
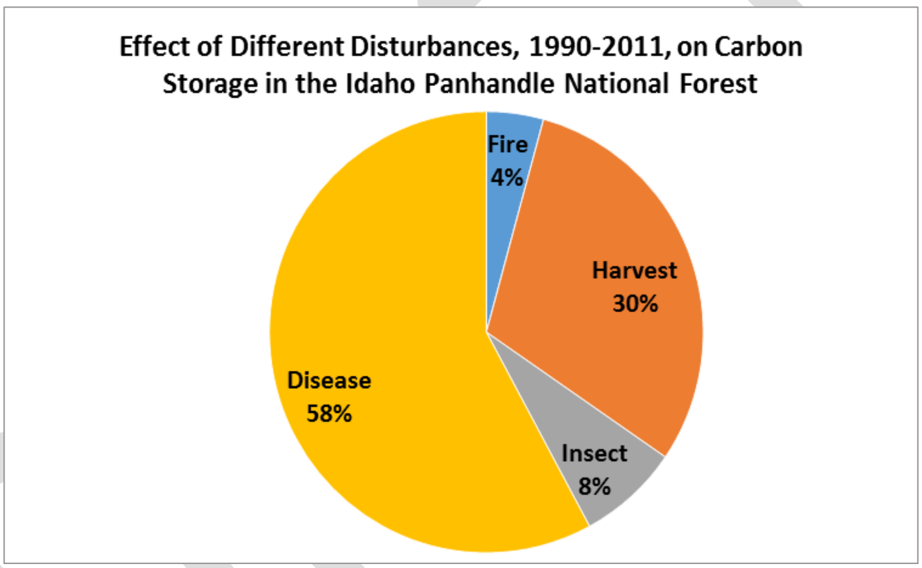
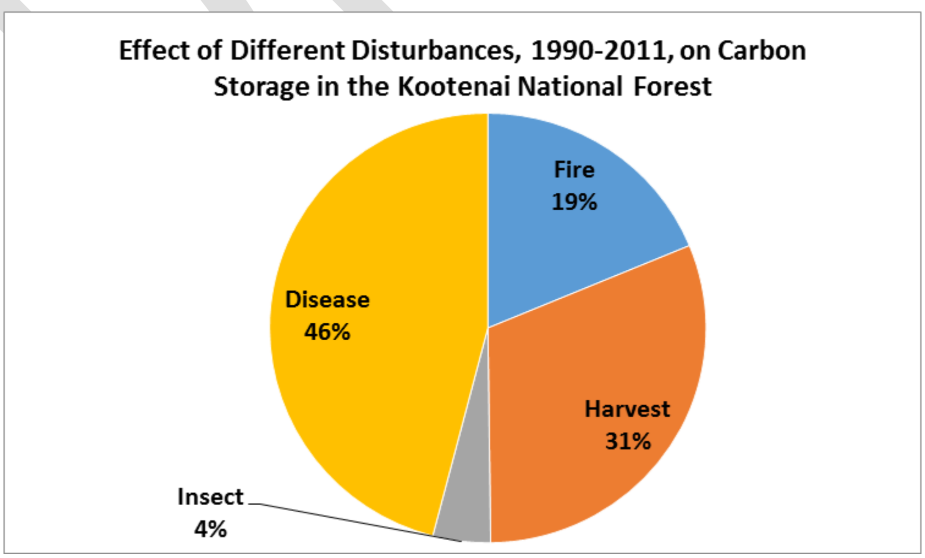
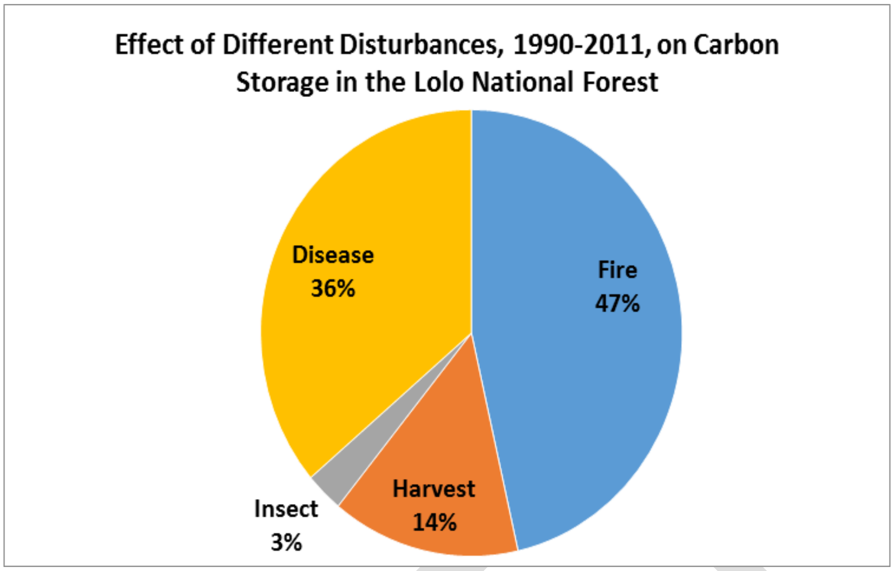


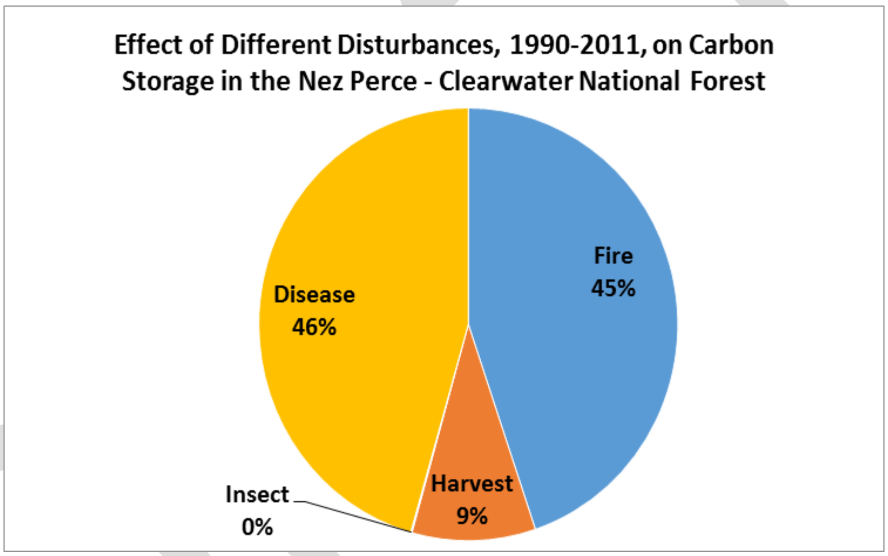
Figure 2. Lost potential storage of carbon as a result of fire, insect, harvest, and disease on each national forest in the Northern Region for the period 1990 – 2011.

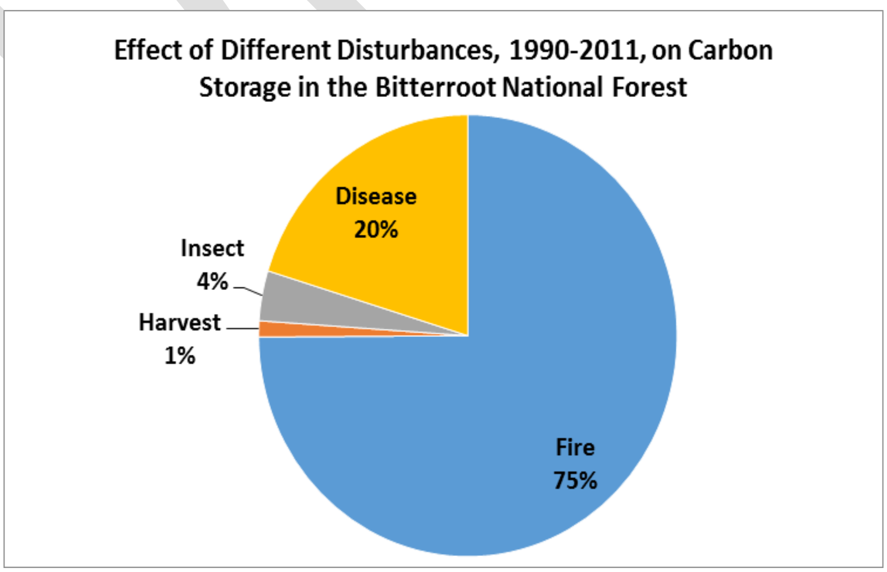

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Flathead National Forest
Disease 35%
Fire 53%
Harvest 10%
Insect 2%

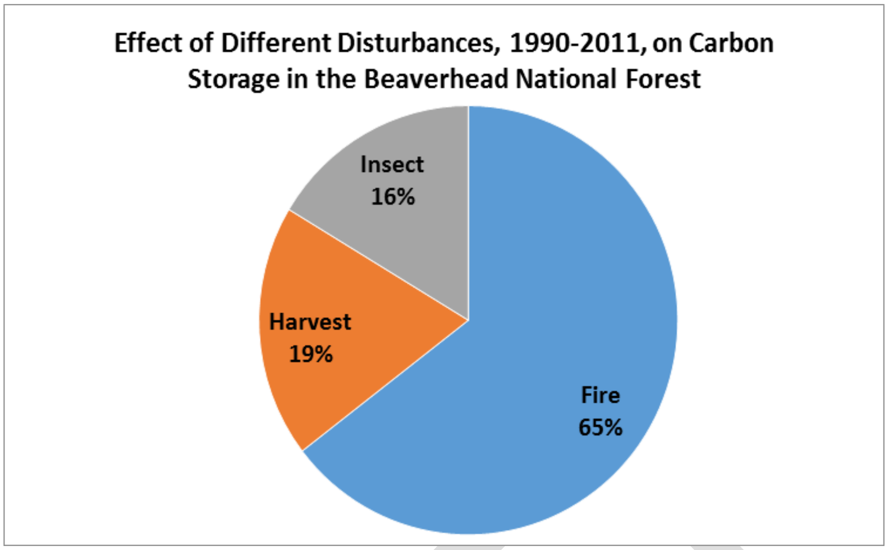

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Idaho Panhandle National Forest
Fire 4%
Harvest 30%
Disease 58%
Insect 8%

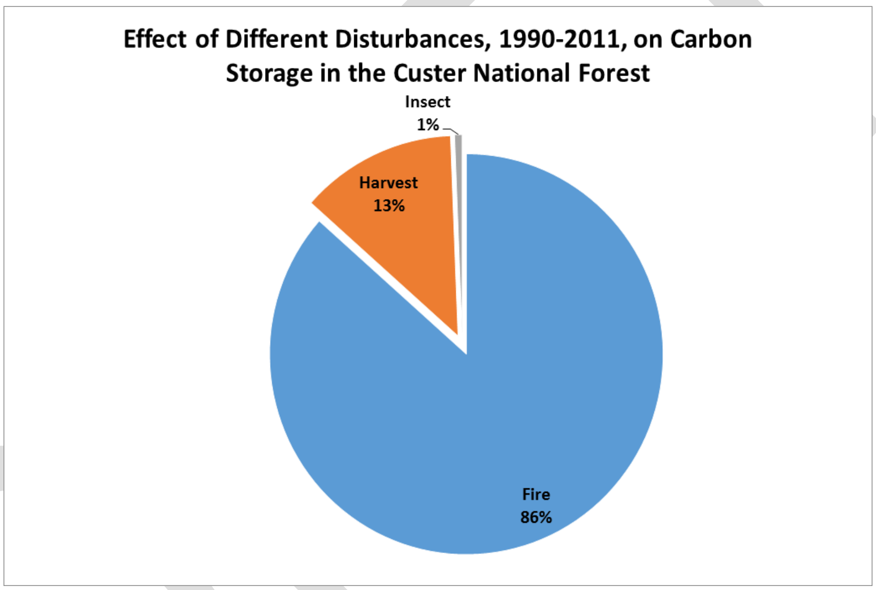

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Kootenai National Forest
Fire 19%
Disease 46%
Harvest 31%
Insect 4%

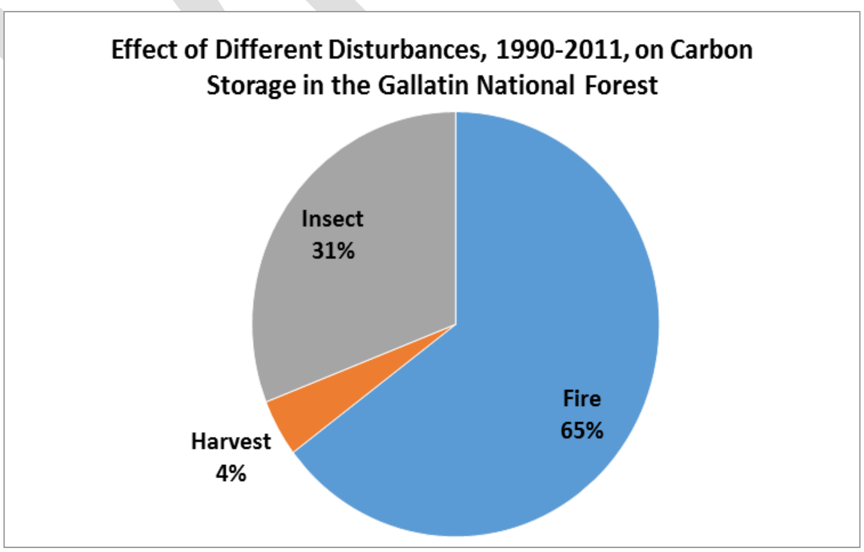

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Lolo National Forest
Disease 36%
Fire 47%
Harvest 14%
Insect 3%

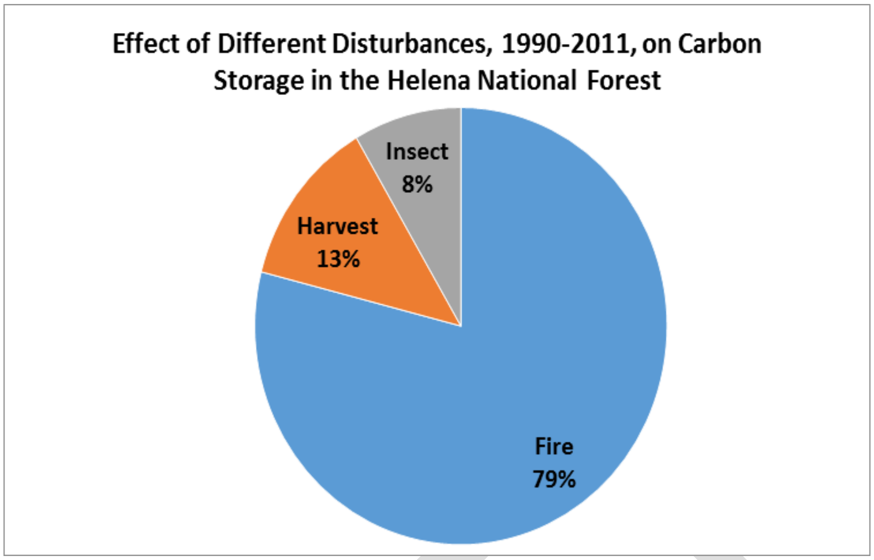

Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Nez Perce - Clearwater National Forest
Fire 45%
Disease 46%
Insect 0%
Harvest 9%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Bitterroot National Forest
Disease 20%
Insect 4%
Harvest 1%
Fire 75%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Beaverhead National Forest
Insect
16%
Harvest
19%
Fire
65%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Custer National Forest
Insect
1%
Harvest
13%
Fire
86%


Effect of Different Disturbances, 1990-2011, on Carbon Storage in the Gallatin National Forest
Insect
31%
Harvest
4%
Fire
65%



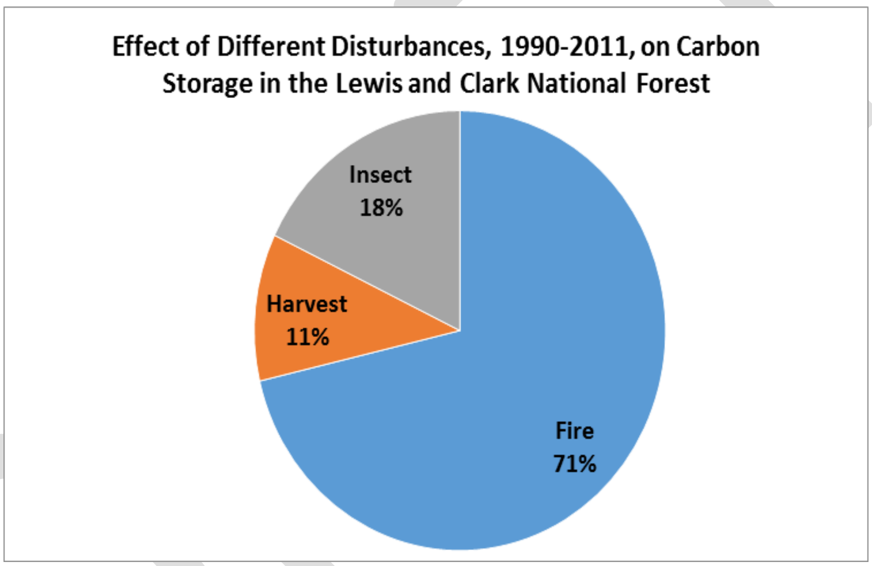


Figure 3. The effect of fire, insect, disease and harvest on carbon storage in each national forest of the Northern Region for the period 1990 – 2011.

12.0 Appendix B: Management implications of ForCaMF results

Earlier baseline assessments (http://www.fs.fed.us/climatechange/advisor/products.html) presented inventory-derived estimates of how much carbon is stored in the forests and in the harvested wood product pools of each national forest. The ForCaMF analyses here focused on how different types and intensities of disturbance have influenced those stocks in recent decades. Specifically, results given in Section 6.1 and Appendix *A* provide details about: 1) patterns of disturbance; 2) how disturbance impacts on carbon storage evolved in each forest from 1990 to 2011, and; 3) the level of uncertainty associated with assessments of each forest. In this section, we bring this information together to answer the simple questions of: "How much do disturbances really disrupt carbon storage?" and "which disturbance processes in each forest are the most important?"

In highlighting what managers and planners can pull from these analyses, it is useful to remember that carbon storage is simply one ecological service, among many, that our forests provide. That service mitigates the climate impacts of greenhouse gases emitted through the use of fossil fuels by removing carbon dioxide from the atmosphere. Figure 1 shows how much less carbon (by percentage) was stored in each forest in 2011 because of different types of disturbance since 1990. Disturbance patterns continue to change, but this assessment of the recent past represents the best available insight into how sensitive national forest carbon storage is to fire, harvest, insects, disease, and weather events. Residual disturbance effects (*e.g.,* decaying dead carbon) of monitored events will depress carbon storage for many years after 2011, just as many pre-1990 disturbances continue to affect current stocks. In most cases, forests re-grow after disturbance and become carbon sinks for many decades or centuries after a relatively short period of reduced carbon stocks. In some regions where carbon stocks have reached elevated levels because of disturbance suppression, a lower level of carbon stock may be more sustainable compared with the recent past.

The period of this snapshot was somewhat arbitrary; however, every analysis needs sideboards, and the period used here coincides with our best monitoring data (satellite imagery, Agency activity records, FIA data). The percentages recorded in Figure 1 may seem relatively small, but they often represent very large amounts of climate mitigation benefit. For instance, if a national forest has half a million hectares of forestland that FIA tells us is storing 50 Mg of carbon per hectare, and ForCaMF tells us that there would be 2% more carbon without insect activity from 1990-2011, that is a difference of half a million metric tonnes (Mg) of carbon, or 1.835 million tonnes of CO2 (using a 3.67 conversion ratio for carbon to carbon dioxide). For perspective, this is approximately the amount of carbon dioxide released by burning around 200 million gallons of gasoline (US Energy Information Administration), and its offset value (amount it would be worth if its continued storage were sold on an open market at a conservative price of $10/tonne) would be almost $20 million.

There are certain ways that Figure 1 does not tell the complete story. The FVS model, which supplies stand dynamics within ForCaMF, does not cover soil organic carbon, and Figure 1's calculations exclude soils. Fortunately, the InTEC model presented in this assessment do provide insight into soil carbon dynamics. More importantly, there are some types of disturbance known to be important that were excluded. For instance, root diseases are known to be prevalent in many parts of the country, but they can be difficult to detect with satellite or aerial imagery because their effects in most years can be limited to reduced growth and suppression of regeneration. ForCaMF was used to assess the impacts of root disease in only 6 national forests, all in the Northern Region. That analysis, which was only possible because of a specialized "regional add-on" variable to core FIA measurements, showed significant root disease impacts that equaled the impacts of fire despite several large fire events in the Region (Healey et al. 2016). We know that we are missing similar processes across the country that are not well addressed by available monitoring data.

Disturbances due to climate variability were assessed with the InTEC model which includes precipitation and temperature as major factors affecting forest processes. The effects of climate variability may be positive or negative, and are often highly variable from year to year, depending on the region and how the climate variables interact to affect photosynthesis and respiration. The effects of climate also interact with other atmospheric changes particularly increasing atmospheric carbon dioxide concentration and nitrogen deposition, both of which typically enhance growth rates of forests. Lastly, this assessment does not consider storage of harvested carbon in product pools. Conversion of forest material to durable wood products defers emissions of the associated carbon until decay or combustion following disposal. Earlier baseline assessments and assessments by Stockmann et al. (2012) quantified carbon stocks in wood products that remain in use or landfills, and work is ongoing to combine ForCaMF and product carbon dynamics models. In the present assessment, however, harvest effects (like the effects of all disturbances) are restricted to ecosystem stocks, a limitation that overstates the emissions of carbon dioxide from harvest from an atmospheric point of view. The effect of substituting wood products for other materials such as concrete and aluminum are not considered in any of the assessments but are potentially significant and will be assessed in future work.

It is outside the scope of this assessment to suggest the importance of ecosystem services associated with carbon relative to other values such as water yield or habitat conservation. What we do provide is tangible information about how management and disturbance prevention/suppression can impact (and has impacted) the climate change mitigation a national forest generates. To the degree planners value carbon storage as a service, the disturbance rates published here, along with resultant carbon storage differences, can frame management goals moving forward.

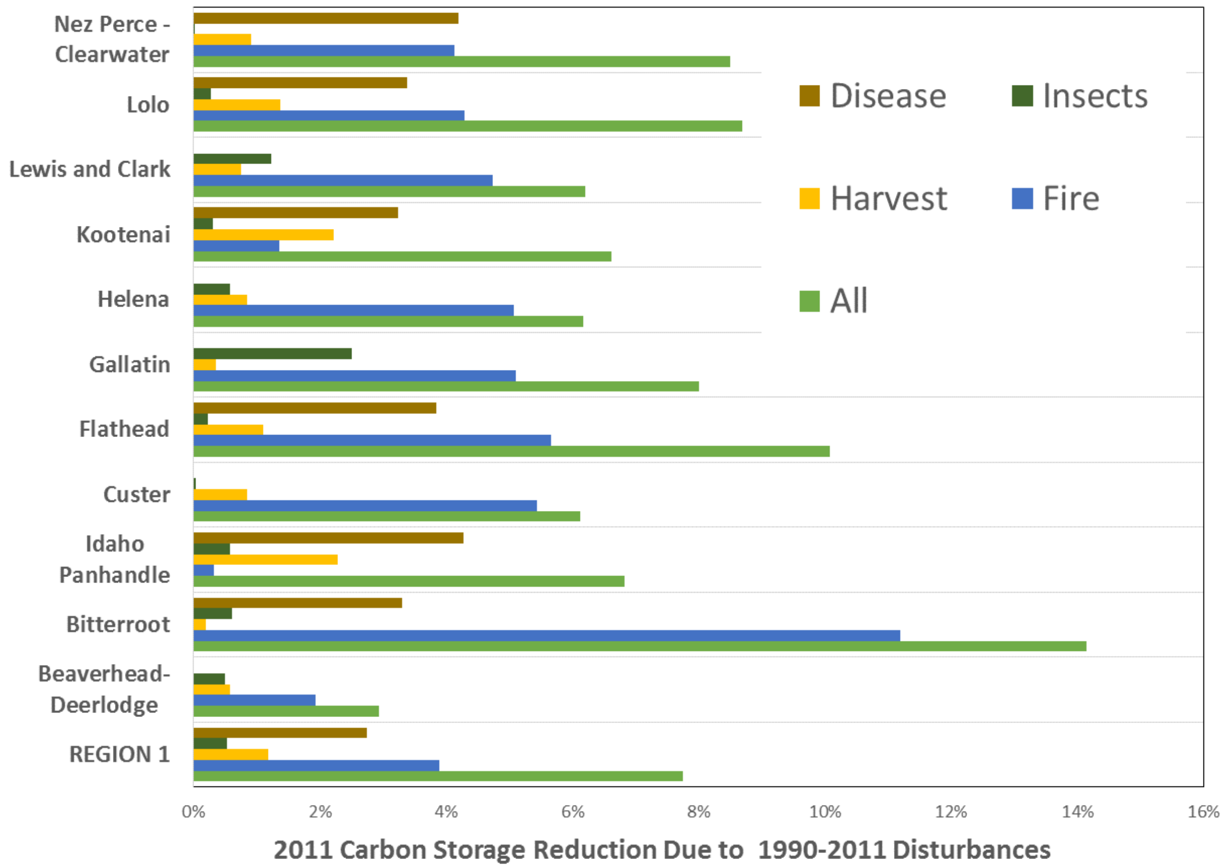


Figure 1. The degree to which 2011 carbon storage on each national forest was reduced by disturbances occurring from 1990 to 2011 in the Northern Region. Results were derived through the ForCaMF system (Healey et al., 2014), and include all non-soil ecosystem pools. In some cases, disturbances classified by wind may actually be from other storm effects, such as ice damage.

13.0 Appendix C: Effects of disturbance, management, and environmental factors (InTEC) for individual National Forests in the Northern Region

The set of figures for each of the 11 National Forests units in the Northern Region were generated from both input datasets and outputs from the InTEC model. The input figures presented here include stand age-dominance type distributions (Figure 1), net primary productivity and stand age relationships (Figure 2), total annual precipitation (Figure 3a), mean annual temperature (Figure 3b), and total annual nitrogen (N) deposition (Figure 3c) from 1950-2010. A single atmospheric CO_2 dataset indicating an increasing trend from 280 ppm in 1901 to 390 ppm 2010 (Keeling et al. 2009) was used for all National Forest units across the U.S. The disturbance type and magnitude figures (Appendix A, Figure 1) are also referenced as they are useful for understanding model results. Summary figures of the input datasets have been included in these assessments because they provide useful context for interpreting the model outputs.

Model outputs presented in this assessments include carbon(C) stock changes and C accumulation due to disturbance and non-disturbance factors, and C emissions due to disturbances alone from 1950-2010. C stock change outputs show the change in C stocks over the course of a year, thus the value in a given year is the difference between total C stocks in that year and total C stocks in the previous year. C stock change in equivalent to Net Biome Productivity (NBP), which is the total photosynthetic uptake of C by the forest minus the loss of C due to autotrophic and heterotrophic respiration and disturbances. The change in C stocks have been attributed to the following effects: (1) individual non-disturbance factors (climate, N deposition, CO_2 concentrations) (Figure 4a), (2) combined disturbances factors (fire, harvests, insects, aging & regrowth) (Figure 4b), (3) combined non-disturbance factors (Figure 4b), and (4) all factors which is the sum of all non-disturbance and disturbance effects (Figure 4c). A positive C stock change value in a given year signifies that the factor(s) caused the forest to absorb more C from the atmosphere than it emitted, thus acting as a C sink. A negative C stock change value indicates that the factor(s) caused the forest to release more C to the atmosphere than it absorbed, thus acting as a C source.

Consecutively summing the annual C stock changes (Figure 4a-4c) yields the total accumulated ecosystem C since 1950 (Figure 4d). Positive values indicate accumulated effects that enhanced the total C stock, and negative values represent accumulated effects that reduced the total C stock. The total C emissions due to disturbances alone are also included (Figure 4e) and when added to the C stock change (NBP), yields the Net Ecosystem Productivity. The results of the InTEC model runs are numerous and include mapped outputs, C densities, and the effects of both non-disturbance and disturbance factors on individual component pools (e.g. aboveground live C, soil C), thus only summary results are presented here.

C.1 Beaverhead-Deerlodge National Forest - Montana

Between 1950 and 2010 forests in the Beaverhead-Deerlodge National Forest transitioned from a C sink to predominantly a C source (Figure 4c). Disturbances/aging has had mostly negative effects on changing C stocks over the past few decades (Figure 4b). This trend is primarily due to an aging effect as more than 75% of the stands are >80 years old (Figure 1) and have aged past their peaks in productivity (Figure 2). The stand age distribution shows a pulse of stands establishing 120-129 years old ago (1881-1890), likely a result of re-establishment following disturbances such as large wildfires or land use change associated with EuroAmerican settlement in the region. Another important factor during the re-growth phase has been fire suppression, which allowed the stands to continue re-growing rather than being disturbed at a more typical historical rate. Depending on the forest type, this establishment pulse would have reached peak productivity around 1930-1950 (Figure 2), which explains the transition from a C sink to a C source in the 1950s (Figure 4b), as losses from decomposition and decay exceeded C gains. As forests recovers from the small, but higher-severity disturbances in 2000 and 2008 (Appendix A, Figure 1g) and reach peak productivity in several decades, they may transition to a C sink again. However, there have been only low-levels of establishment of young stands (Figure 1) and forests have remained a C source (Figure 4b-c).

Of non-disturbance factors, climate has had the strongest effect on changing C stocks, with effects being mostly negative since the late 1990s (Figure 4a). The overall increasing trend in mean temperatures (Figure 3a) may have increased soil respiration and water stress, negatively affecting total C stocks, but not to the extent of disturbance/aging effects (Figure 4d). The increases in nitrogen deposition (Figure 3c) and atmospheric CO_2 concentrations enhanced the C sink (Figure 4a), causing an increase in accumulated C since 1950 (Figure 4d), but were not enough to offset the C losses due to disturbances, aging, and climate. Overall, Beaverhead-Deerlodge National Forest experienced a net loss of approximately 25.2 Tg C from 1950-2010 (Figure 4d), mostly due to disturbances and aging stands, followed by negative climate effects (Figure 4d).

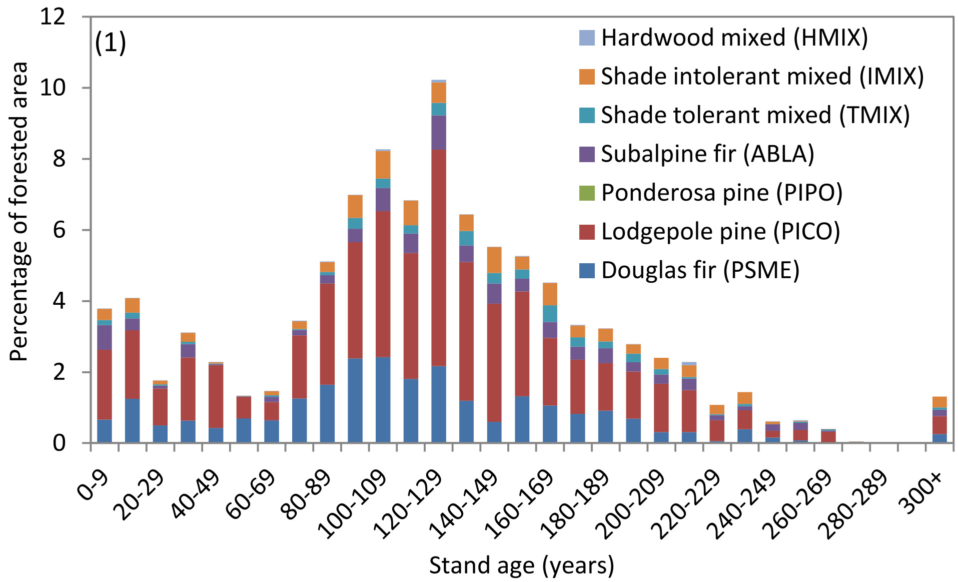


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

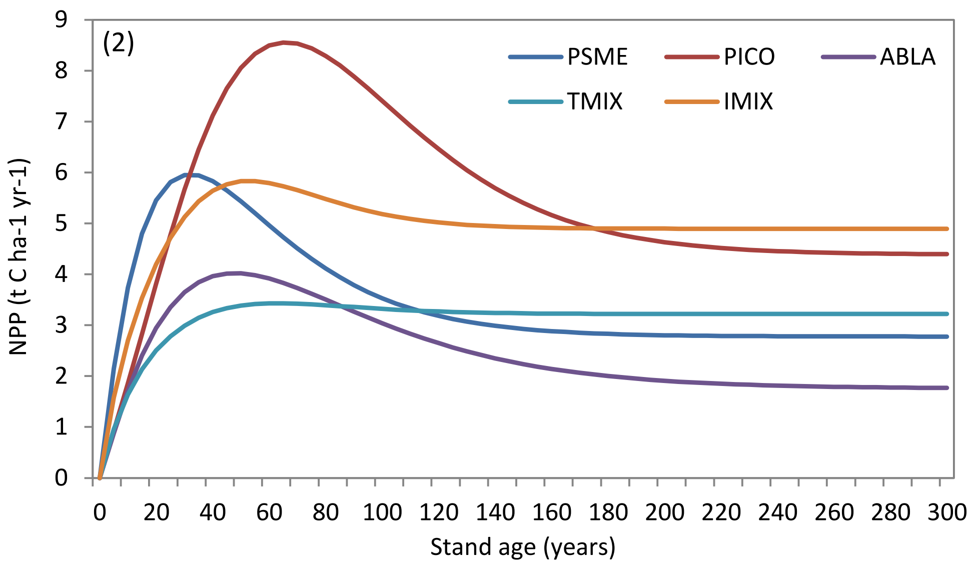


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX). Note: There was not an adequate sample of Ponderosa pine (PIPO) or hardwood mixed (HMIX) plots to derive NPP-age curves, thus the IMIX curve was used for the few PIPO and HMIX stands.

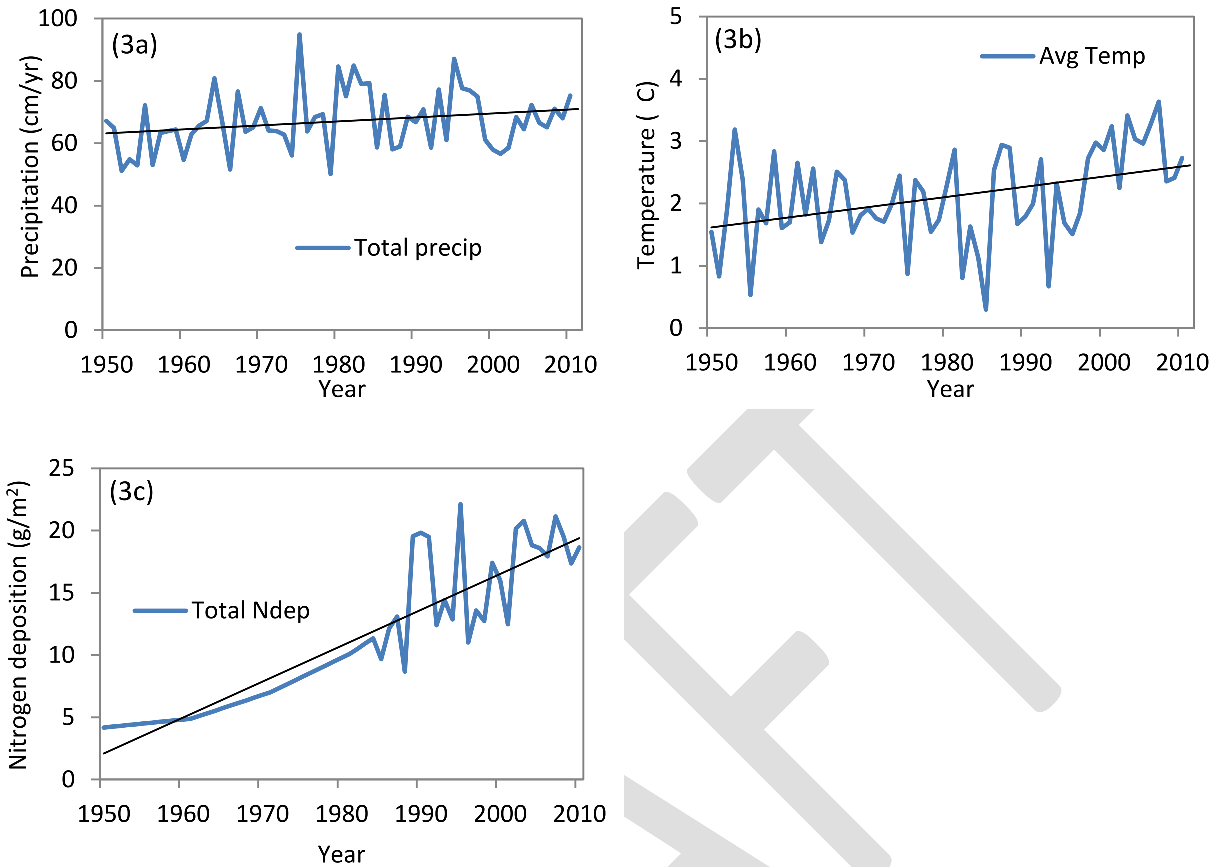


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

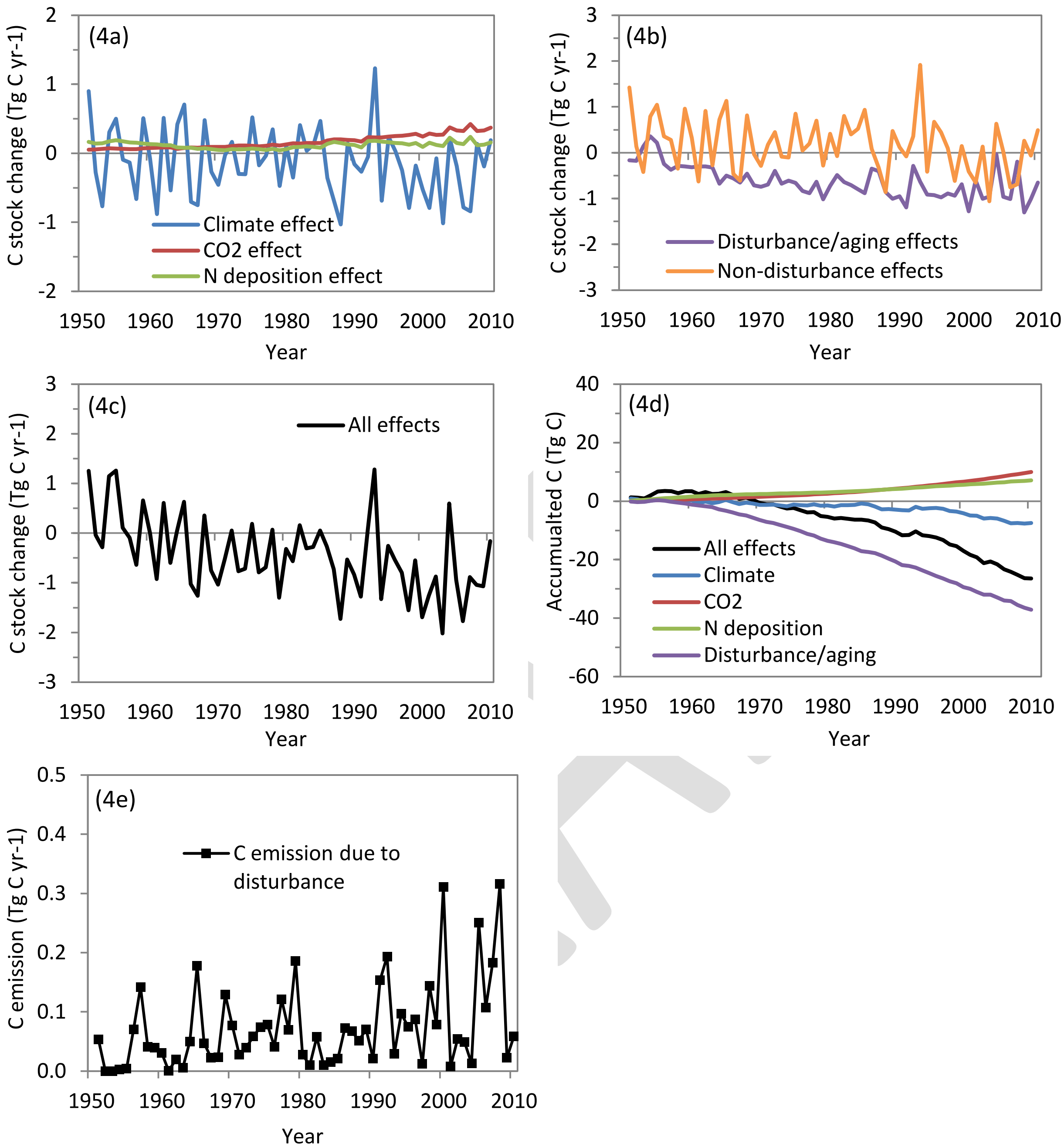


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.2 Bitterroot National Forest - Montana & Idaho

Between 1950 and 2010, forests in the Bitterroot National Forest transitioned from a C sink to mostly a C source (Figure 4c). Disturbance/aging has had a negative effect on C stocks, enhancing the C source since 1950 (Figure 4b). This is primarily due to aging forests, as roughly 65% of the stands are >80 years old (Figure 1) and have aged past their peak productivity (Figure 2). The pulse of stand establishment occurring 90-99 years ago (1911-1920), consisting of primarily Douglas-fir, would have reached maximum productivity in the 1940s (Figure 2), which supports the transition from a C sink to a source thereafter in the 1950s (Figure 4b), as C losses from decomposition and decay became greater than C gains. This pulse may be a result of recovery after major fires and/or increased disturbances associated with settlement activities, as well as fire suppression which allowed more young trees to survive than if normal disturbance rates continued. High severity fires in 2000, which affected > 10% of the forest (Appendix A, Figure. 1f), caused the emission of 1.2 Tg C (Figure 4e), and the forests to become a significant C source (Figure 4b-c). Bitterroot NF is starting to recover from this fire, evidenced by the significant pulse of young tree which established between 2000 and 2010 (Figure 1). The ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Appendix A, Figure 2f). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger C source since 1990 than the InTEC results indicate.

Climate has also had a negative effect on changing C stocks (Figure 4c) and C accumulation (Figure 4d), due to warmer temperatures (Figure 3b) and a decrease in precipitation (Figure 3a). Warmer temperatures increase respiration while drought conditions cause water stress and constrain growth. The increases in nitrogen deposition (Figure 3c) and atmospheric CO_2 enhanced the C sink, but were overshadowed by the C losses due to disturbances, aging, and climate. Overall the Bitterroot NF experienced a net loss of approximately 16.2 Tg C since 1950 (Figure 4d), mostly due to negative disturbance/aging and climatic effects (Figure 3d). When taking into account potential C losses due to recent disease impacts (Appendix A, Figure 2f), Bitterroot NF likely experienced a larger net loss in total C stocks.

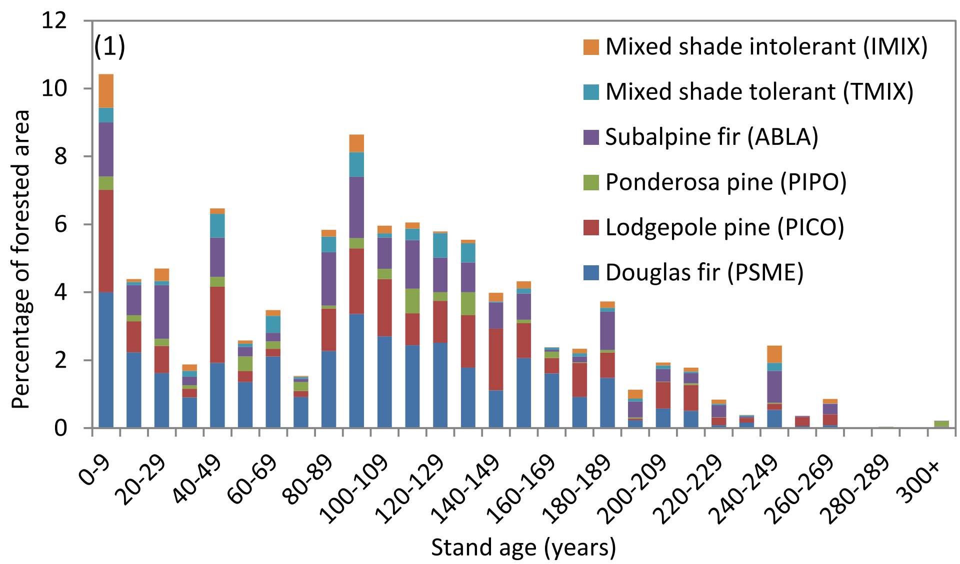


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

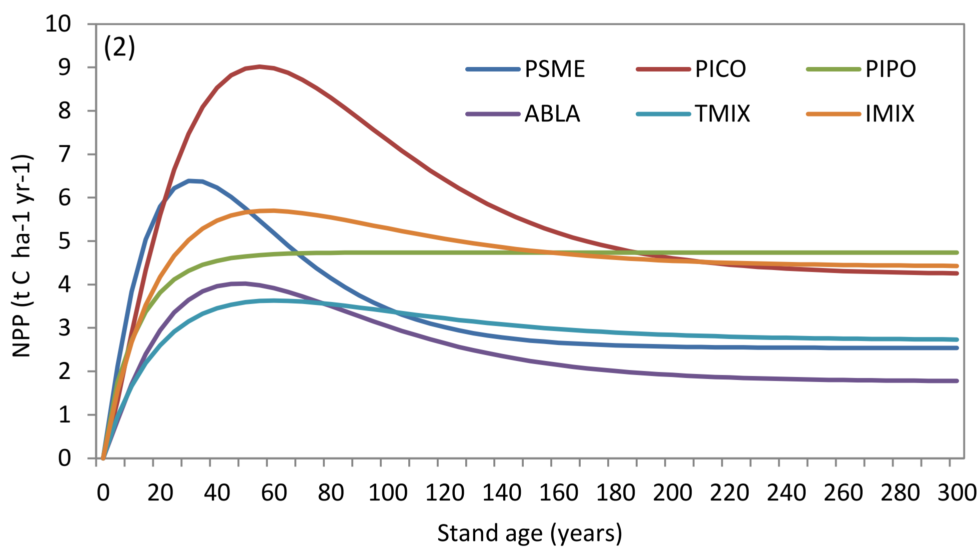


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

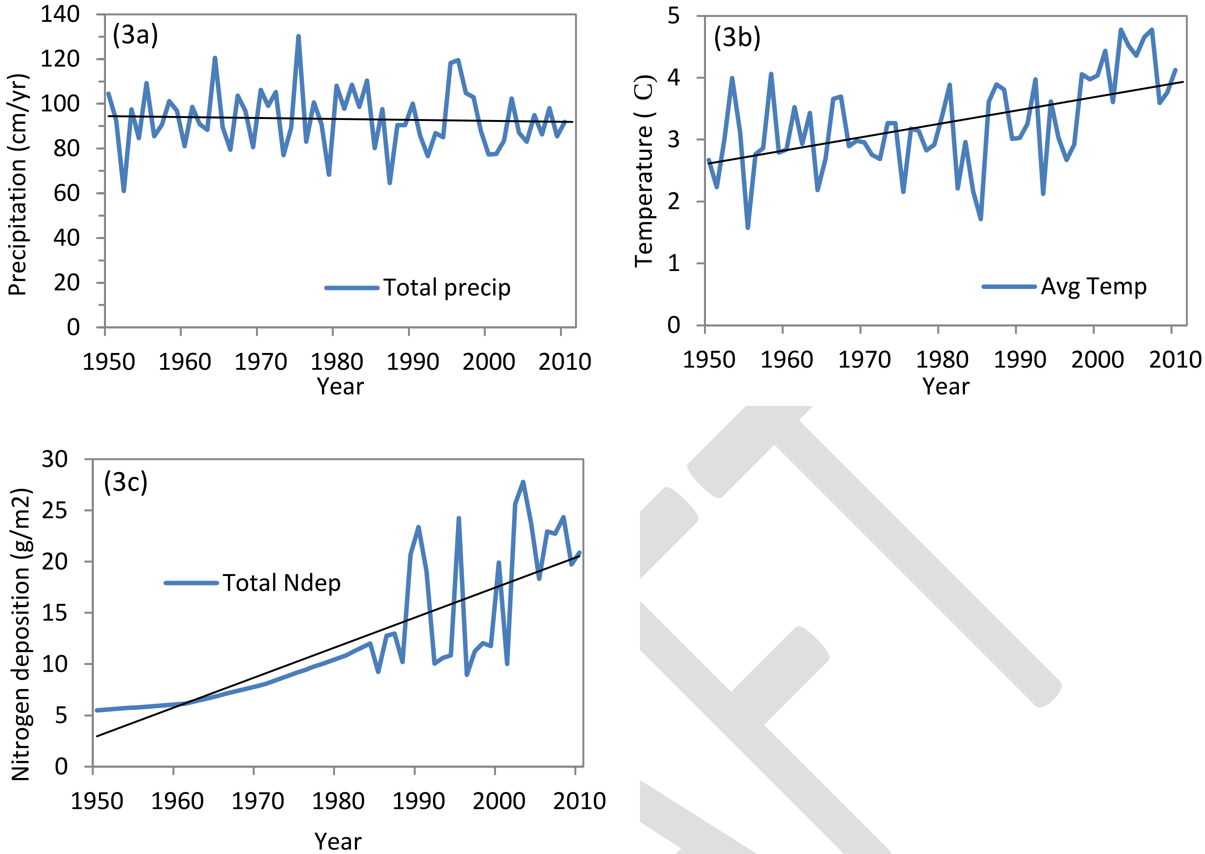


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

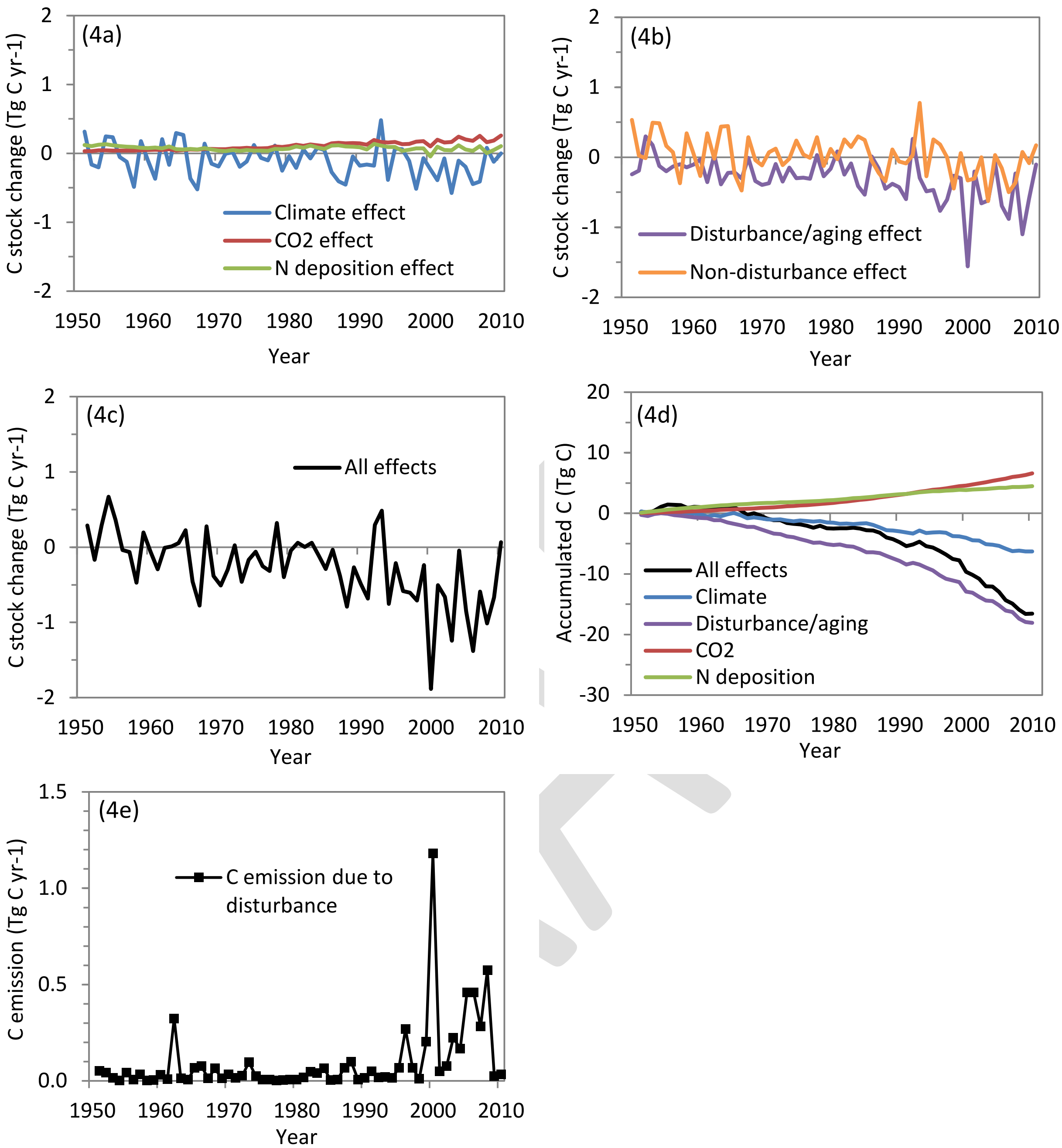


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.3 Custer National Forest - Montana, South Dakota & North Dakota

From 1950-1993, forests in the Custer NF maintained a small carbon (C) sink, but then switched to mostly a C source due to recent disturbances (Figure 4a-c). Roughly 22% of the forests in Custer NF are young (<10 year old), reflecting establishment and regrowth after significant fire and harvest disturbances in 2006, 2008, and 2009 (Appendix A, Figure 1h). As the predominantly young, Ponderosa pine stands (Figure 1) approach middle-age (~35 years old) they will be growing at peak productivity suggesting C stocks may accumulate most rapidly in approximately two decades (Figure 2), and forests have the potential to switch to a C sink again. The negative influence of disturbances in the 2000s (Figure 4b) suggests that the forests have not yet recovered C from these recent disturbances.

Climate variability caused the forest to fluctuate between a C sink and source over this period. However, over the past two decades climate effects on changing C stocks have been mostly negative (Figure 4a), likely due to warming temperatures (Figure 3b) causing increased soil respiration and water stress. The increases in nitrogen deposition (Figure 3c) and atmospheric CO_2 concentrations enhanced the C sink, helping forests to accumulate C since 1950 (Figure 4d). Despite recent C losses due to disturbances and climate, CO_2 fertilization and nitrogen deposition partially offset these losses and ultimately enabled the forest to achieve a net gain of approximately 6.4 Tg C from 1950-2010 (Figure 4d).

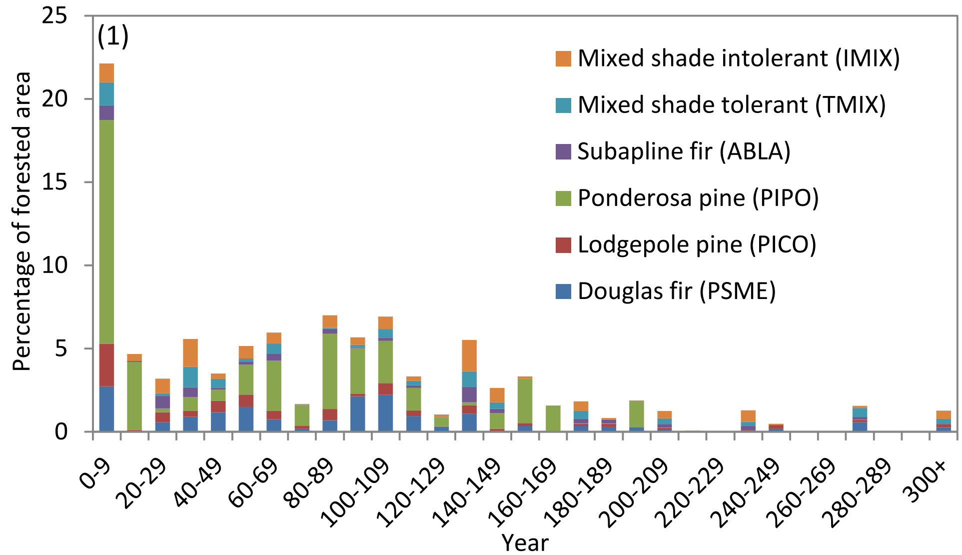


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

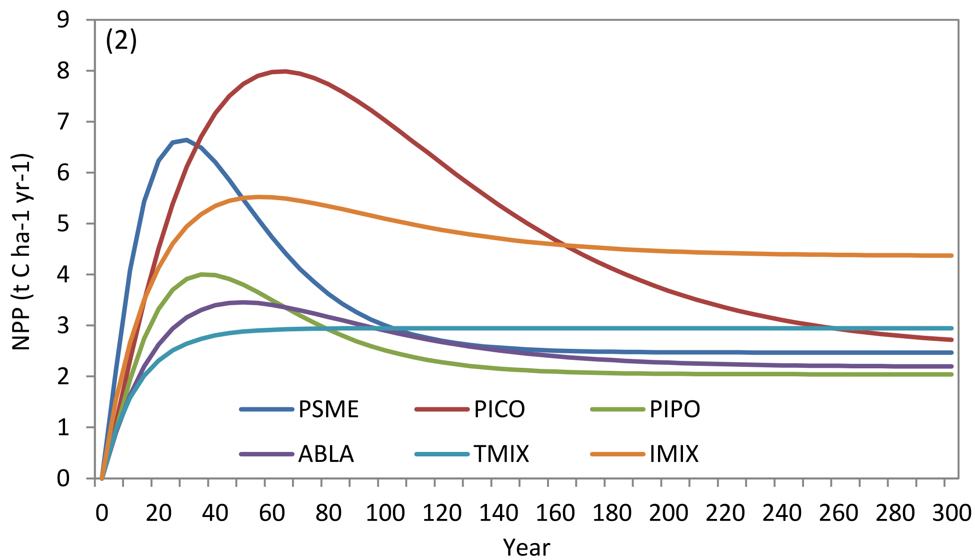


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

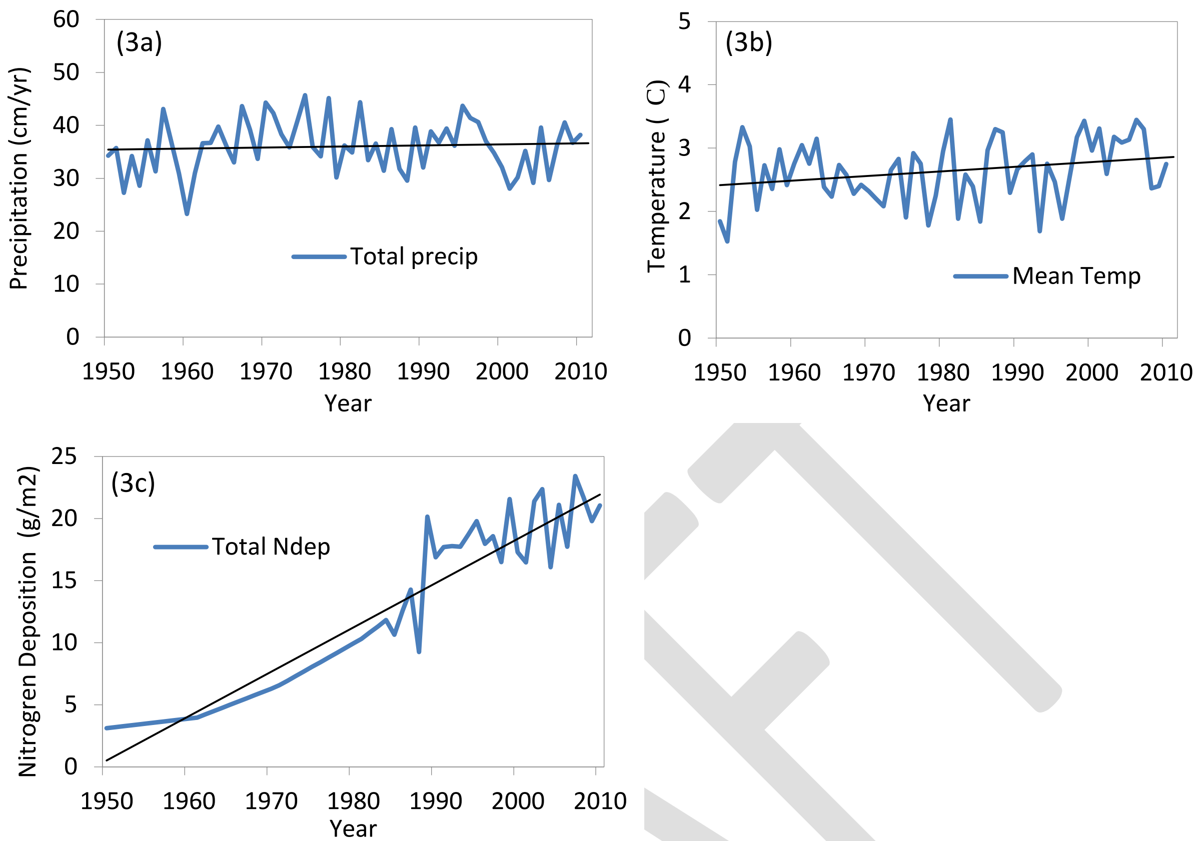


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

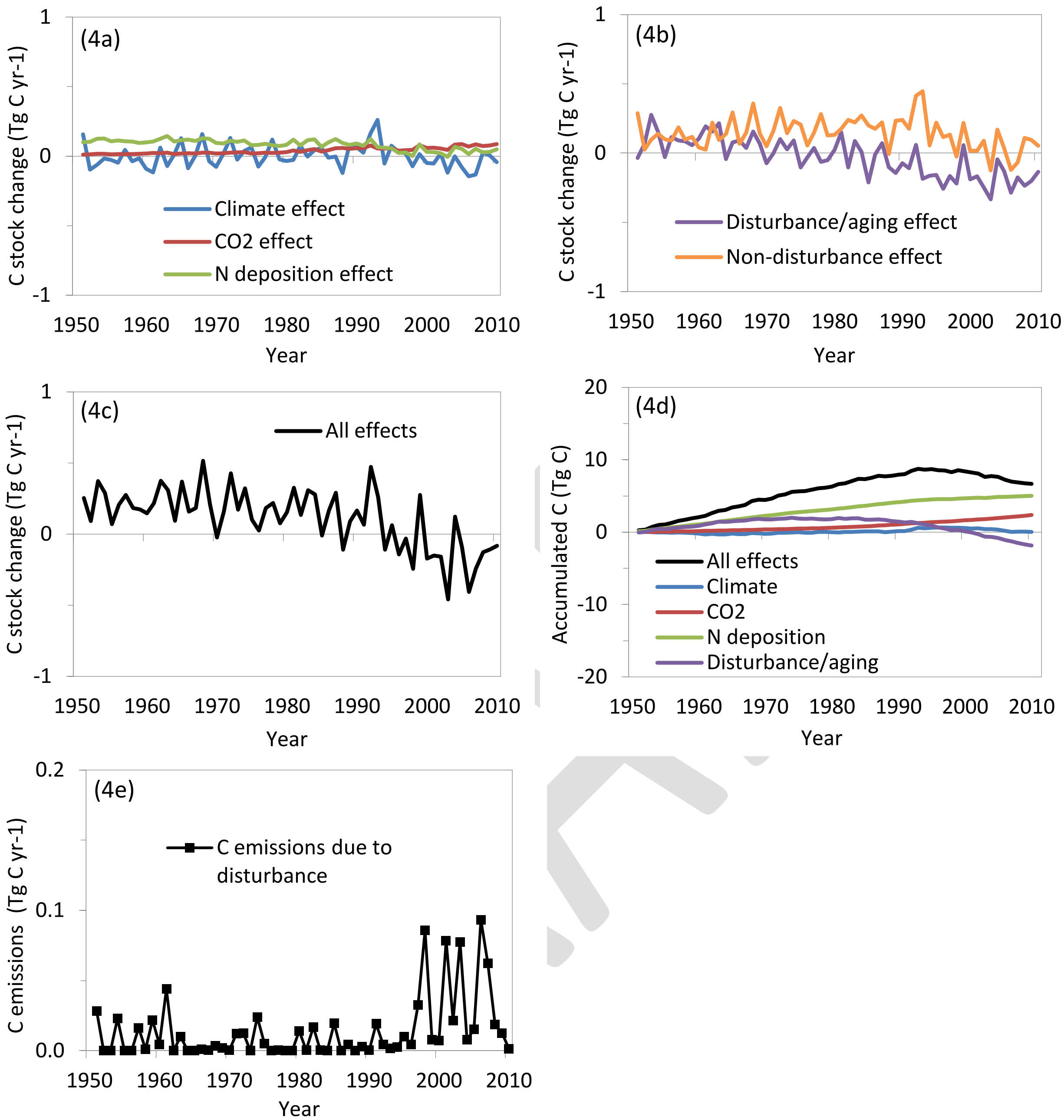


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.4 Flathead National Forest - Montana

Despite periodic C sink years, forests in the Flathead NF have more often been a C source (Figure 4c), experiencing an overall decline in C stocks between 1950 and 2010, due to negative disturbance/aging and climatic effects (Figure 4d). In the 1950s and 1960s disturbance/aging effects enhanced the C sink (Figure 4b), likely due to recovery from early 20th century disturbances, evidenced by the pulse of stand establishment 80-90 years ago (Figure 1). Also, fire suppression during this period allowed stands to survive and continue to re-grow, rather than being disturbed at a more typical historical rate. These mostly Subalpine fir and Douglas fir stands (Figure 1) would have reached maximum productivity when they were middle-aged, approximately 35-60 years old (Figure 2) or in the mid-1900s , corresponding to the C sink years (Figure 4b) and period of positive C accumulation (Figure 4c).

From 2000-2009 disturbance/aging effects caused Flathead NF to be C source (Fig 4b), as C emissions also dramatically increased (Figure 4e) due to moderate-to high-severity disturbances throughout much of the 2000s—the largest of which were in 2004 and 2007 (Appendix A, Figure 1a). The ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Appendix A, Figure 2a). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger C source than the InTEC results indicate. These recent disturbances are also reflected in the pulse of young stands (<10 years old) (Figure 1), causing the forest to become a C sink again in 2010. The newly established stands will soon reach their maximum productivity (Figure 2), thus there is the potential for an increase in C accumulation in coming decades.

Of the non-disturbance factors, climate has had a predominantly negative effect on C stocks since the late 1950s, due to increasing temperatures and decreasing precipitation (Figs. 3a-b), which result in greater soil respiration and water stress, constraining growth. Nitrogen deposition and atmospheric CO_2 concentrations have had increasingly positive impacts (Figs. 4a, d), though these were overshadowed by the negative disturbance/aging and climate effects, resulting in a net decline of approximately 13.5 Tg C since 1950 (Figure 4d). When taking into account potential C losses due to recent disease impacts (Appendix A, Figure 2a), Flathead NF likely experienced a larger net loss in total C stocks.

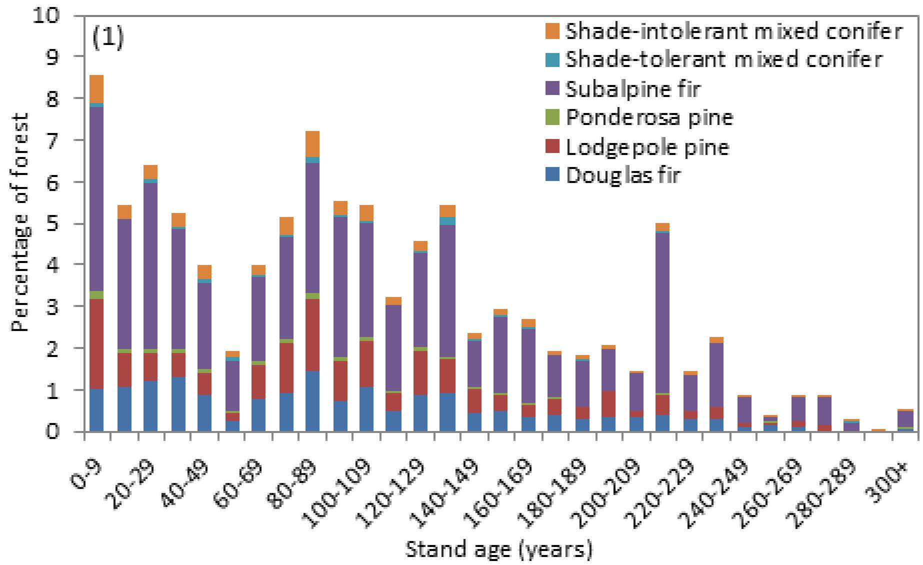


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

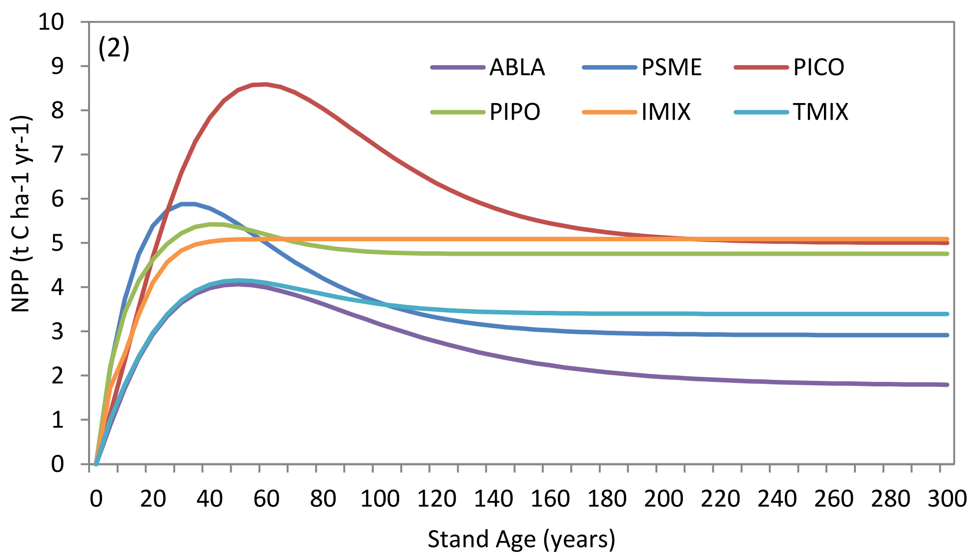


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

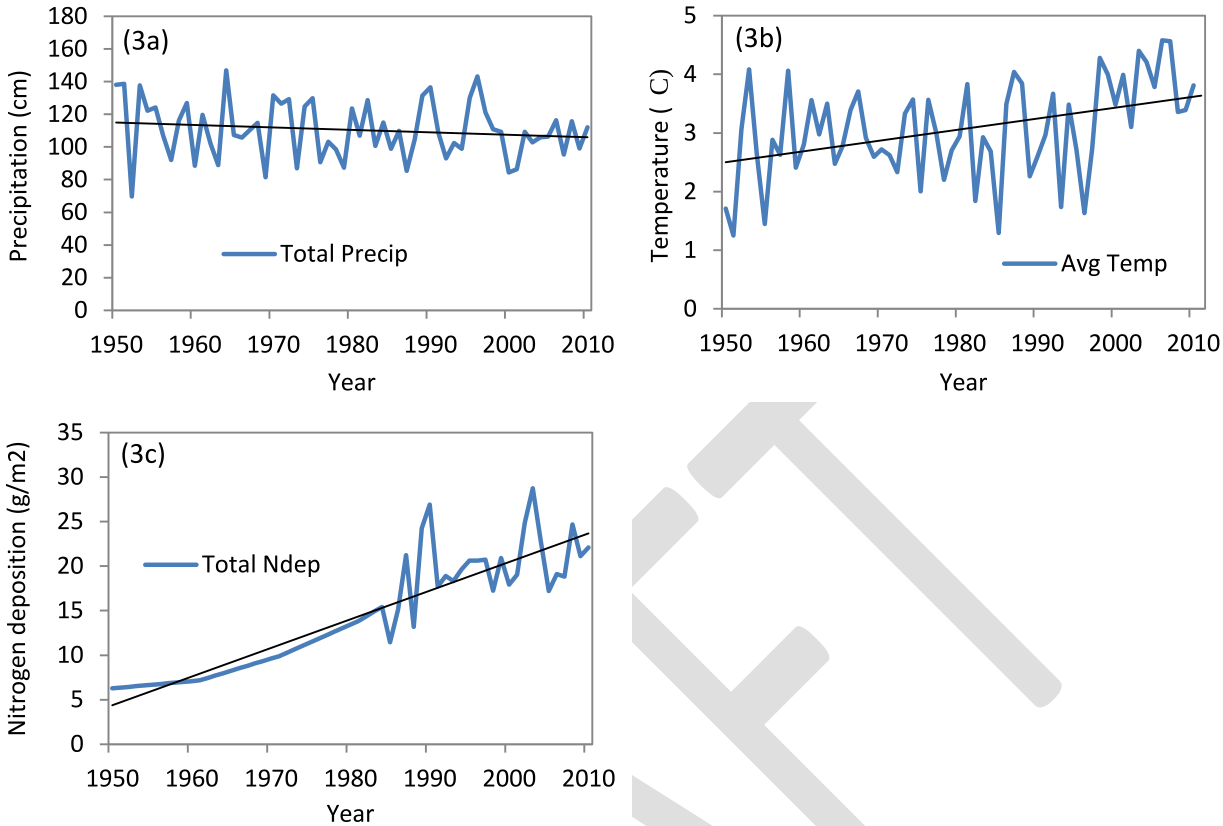


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

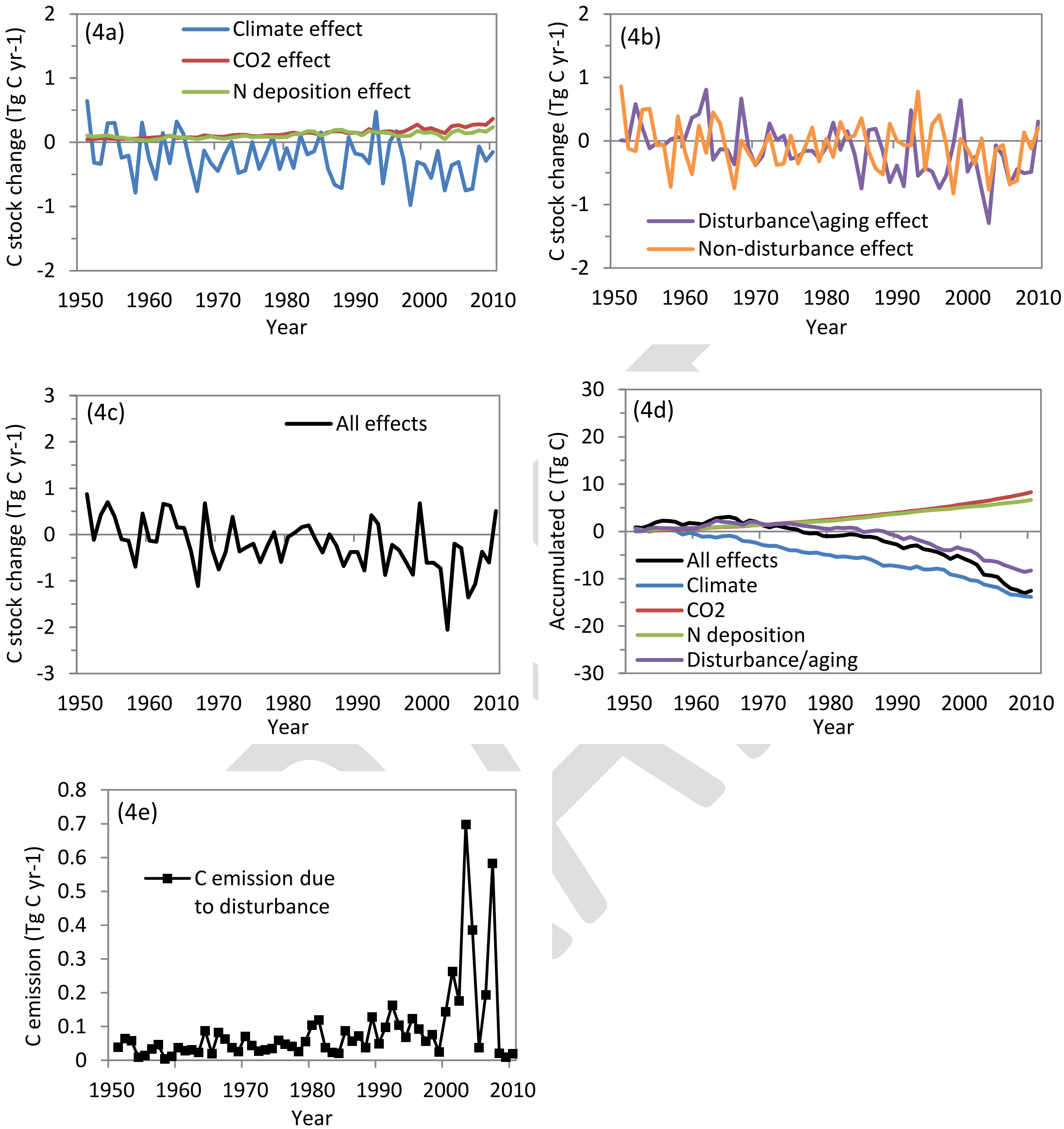


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.5 Gallatin National Forest - Montana

Between 1950 and 2010, forests in the Gallatin National Forest maintained a small carbon (C) source, and experienced a downward trend in changing C stocks (Figure 4c), mostly due to negative disturbance/aging effects (Figure 4b). The stand age distribution indicates that approximately 66% of the stands are >90 years old, with a subtle pulse of stands establishing about 110-139 years ago (1871-1900) (Figure 1), likely as a result of major fires or land-use change associated with Euro-American settlement in the region. Fire suppression activities beginning in the early 20th century then enabled stands to survive and continue re-growing rather than being disturbed at a more typical historical rate. These middle-older aged stands have aged past their peak in NPP and have been declining in productivity (Figure 2) contributing to the decline in forest C from 1950-2010 (Figure 4d), as C losses from decomposition and decay were greater than C gains. About 17% of the stands consist of young forests, <20 years old (Figure 1), indicative of establishment and recovery after recent, large disturbances, especially the fires and insect outbreaks in 2001 and 2006-2008 (Appendix A, Figure 1i). Although these recent disturbances caused an immediate loss of C through direct emissions to the atmosphere (Figure 4e), this pulse of young stands indicates that forests are recovering and have the potential to become a C sink within a few decades, especially as they age to maximum productivity (Figure 2).

Increases in atmospheric CO_2 concentrations and nitrogen (N) deposition (Figure 3c) have had positive effects on C stocks, while climate effects fluctuated between positive and negative following the inter-annual variability in climatic variables (Figure 3a-b). From 1994-2010, climate effects were consistently negative, as a result of warming temperatures which can increase soil respiration and water stress, hampering growth. Despite C accumulation from CO_2 fertilization and N deposition, forests in Gallatin NF experienced a net loss of approximately 14 Tg C from 1950-2010, due to negative disturbance/aging and climate effects (Figs. 4d).

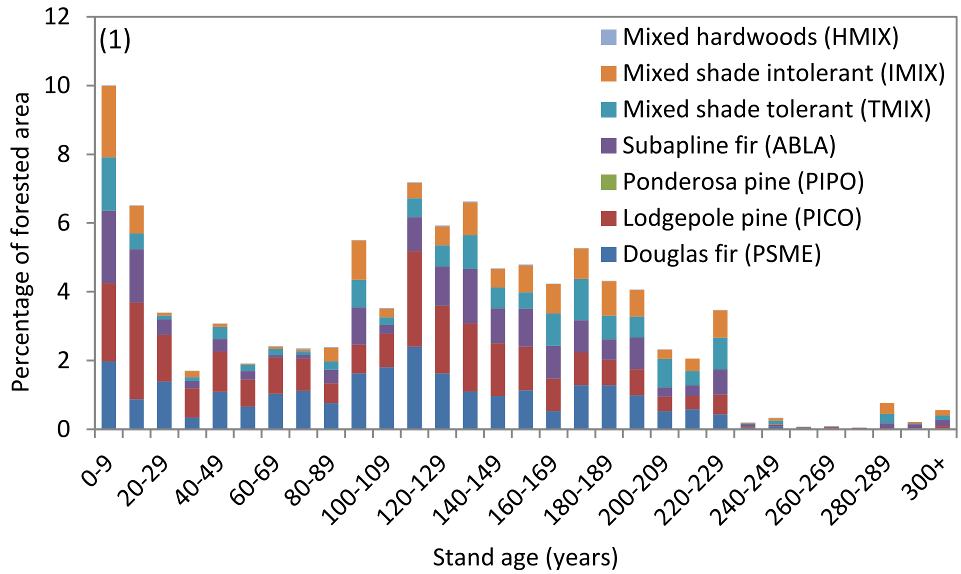


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

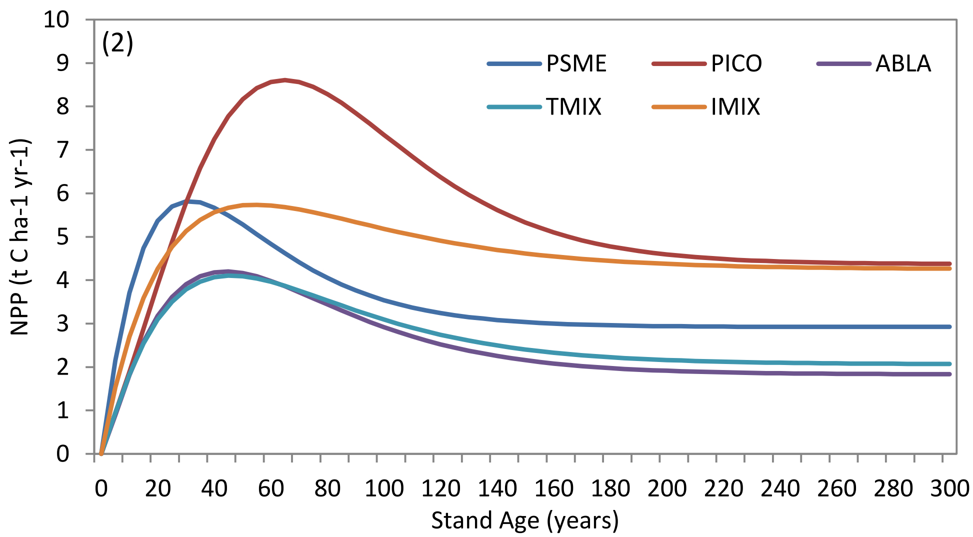


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX). Note: There was not an adequate sample of Ponderosa pine (PIPO) or mixed hardwoods (HMIX) plots to derive NPP-age curves, thus the IMIX curve was used for any PIPO and HMIX stands.

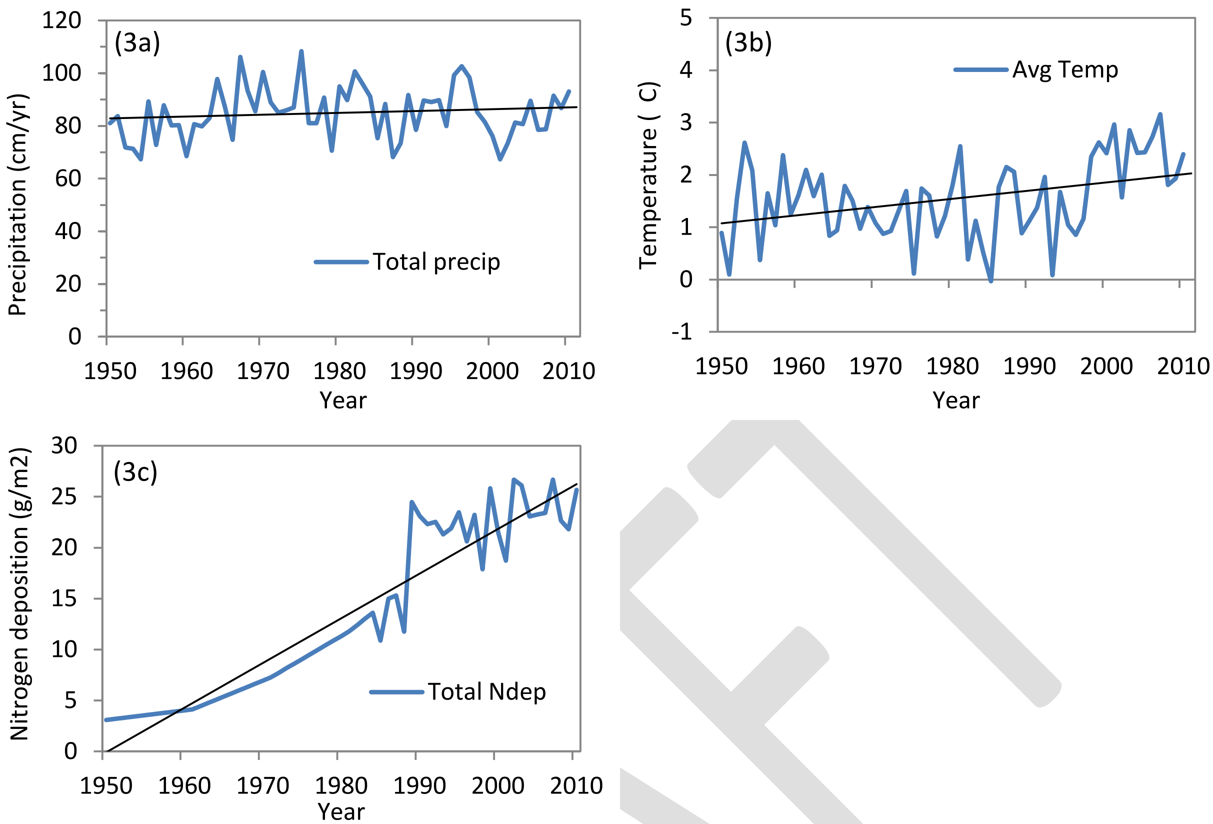


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

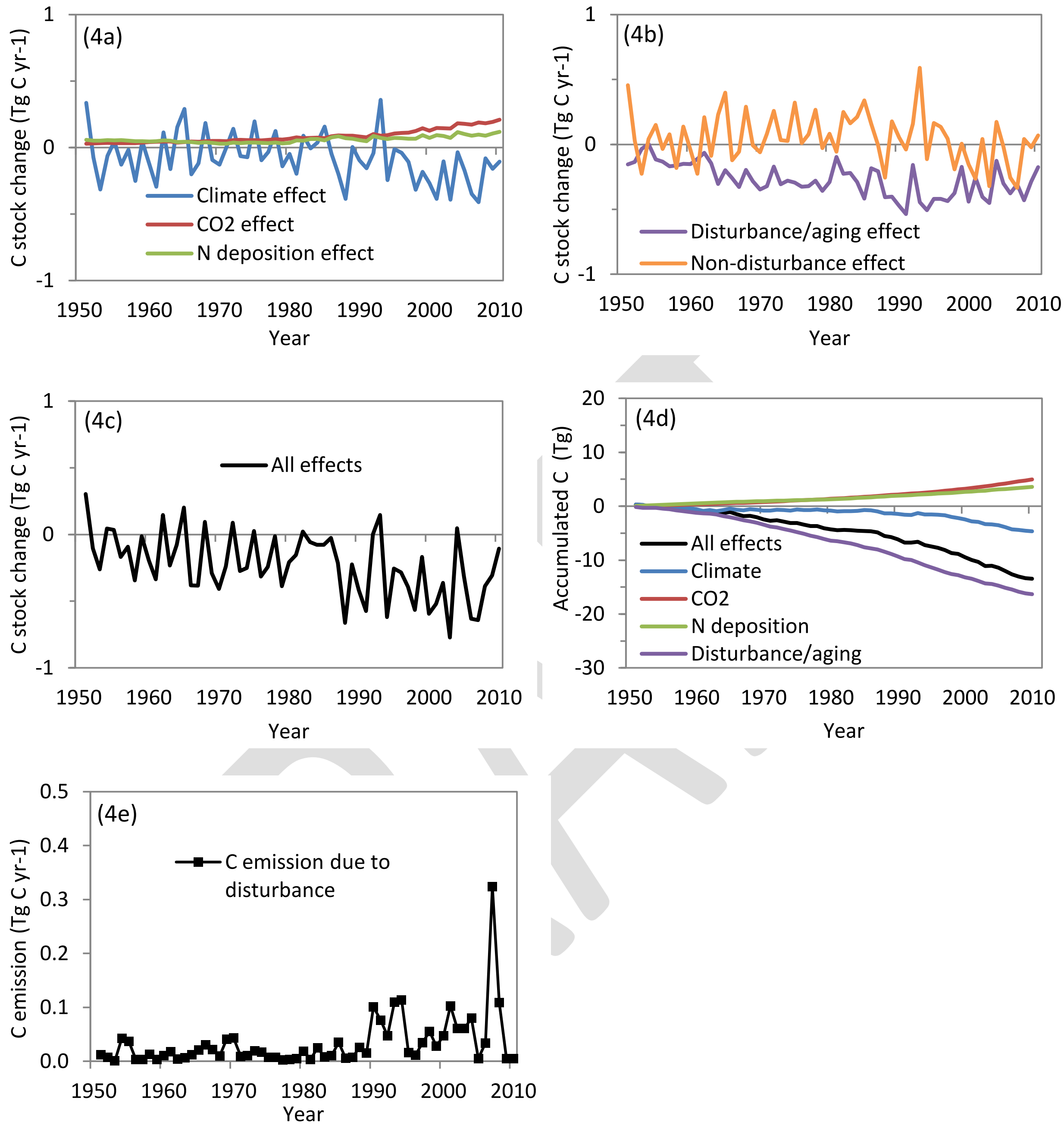


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.6 Helena National Forest - Montana

Forests in the Helena National Forest were a carbon (C) sink from 1950-1993 then switched to a C source through 2010 (Figure 4c). This shift from a C sink to a source corresponds to the increased negative effects of disturbances and aging (Figure 4b), as well as negative climate effects (Figure 5a). The disturbance and aging effects are supported by the stand age distribution which shows a distinct pulse of stand establishment occurring 80-120 years ago (1890-1930), likely due to recovery from the last major fires and/or disturbances associated with Euro-American settlement in the late 1800s (Figure 1). Fire suppression activities beginning in the early 20th century would have also enabled these stands to continue re-growing rather than being disturbed at a more typical historical rate. This pulse of predominantly Douglas-fir and Lodgepole pine stands (Figure 1) would have been growing at peak productivity between ages 30-65 (Figure 2), which corresponds to the increasing C accumulation and the C sink during much of the mid-1900s (Figure 4b, d). Another establishment pulse consists of young stands, <20 years old (Figure 1), resulting in part from the large high-severity fires in 2003 and 2007 (Appendix A., Figure 1j). As these young stands reach middle-age in coming decades, the rate of productivity and subsequent C accumulation will likely increase (Figure 2), thus the Forest has the potential to become a C sink again.

Climate has had a slight negative effect on changing C stocks and accumulation since the late 1960s (Figure 4a, d). Warmer temperatures (Figure 3b) and a slight decrease in precipitation (Figure 3a) caused a greater decrease in C during the 21st century (Figure 4d) than previous decades. Warmer temperatures increase respiration while droughts limit growth. Nitrogen deposition and atmospheric CO_2, which both increased over the past few decades (Figure 3c), had positive effects on changing C stocks and C accumulation (Figure 4a, d). C gains from N deposition and CO_2 fertilization offset C losses due to climate and disturbances, causing total C stocks in 2010 to be about equal to those in 1950.

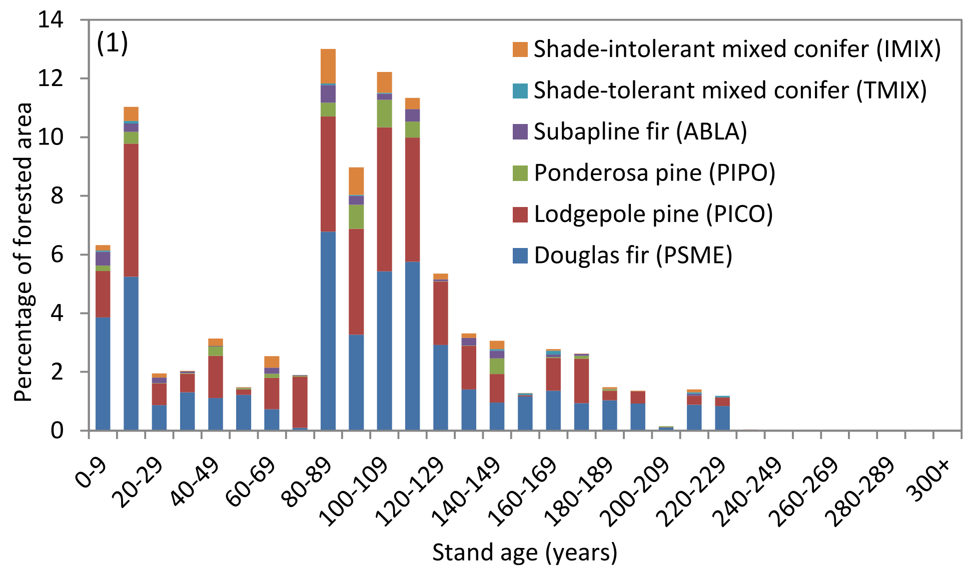


Figure 1. Age class distribution in 2010 displaying the number of forested pixels of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

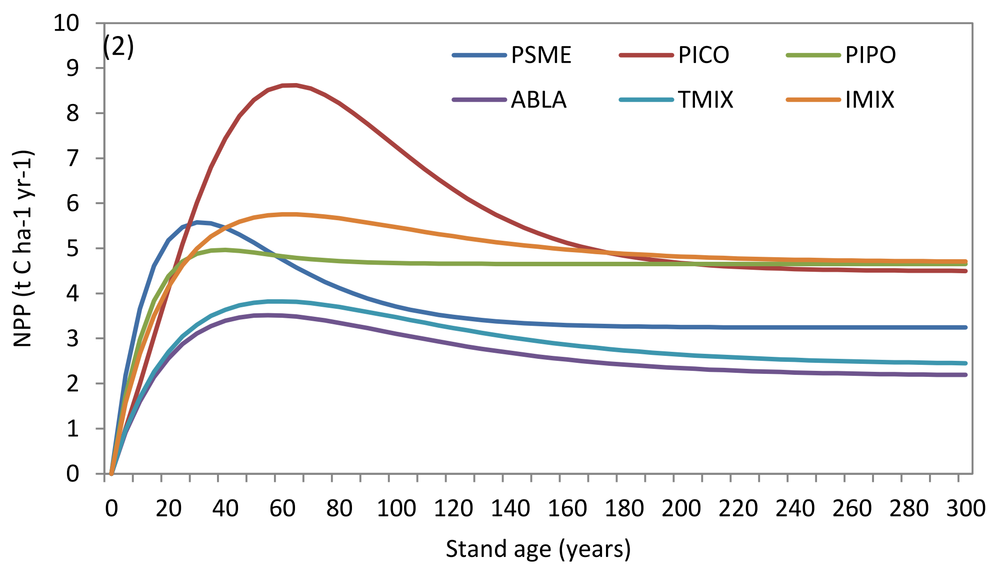


Figure 2. Net primary productivity (NPP)-stand age relationships for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

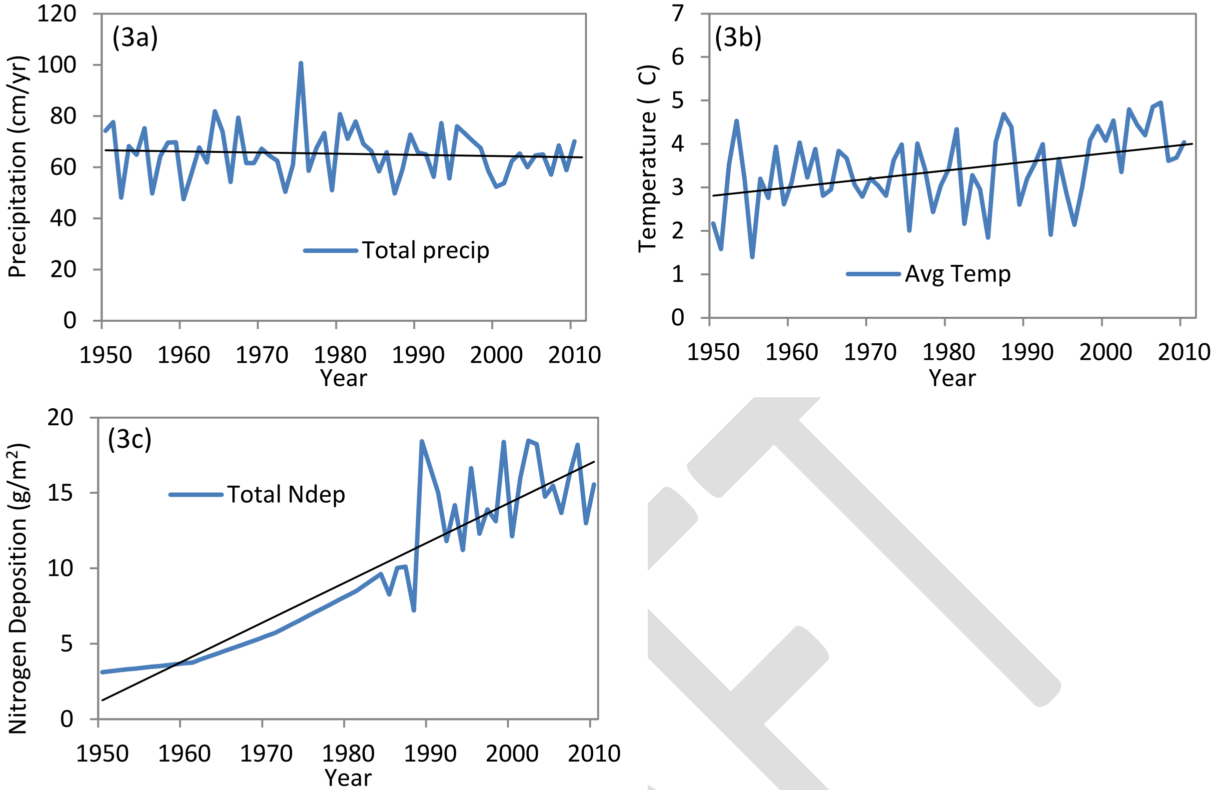


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition (g/m^2) from 1950-2010. Linear trend line shown in black.

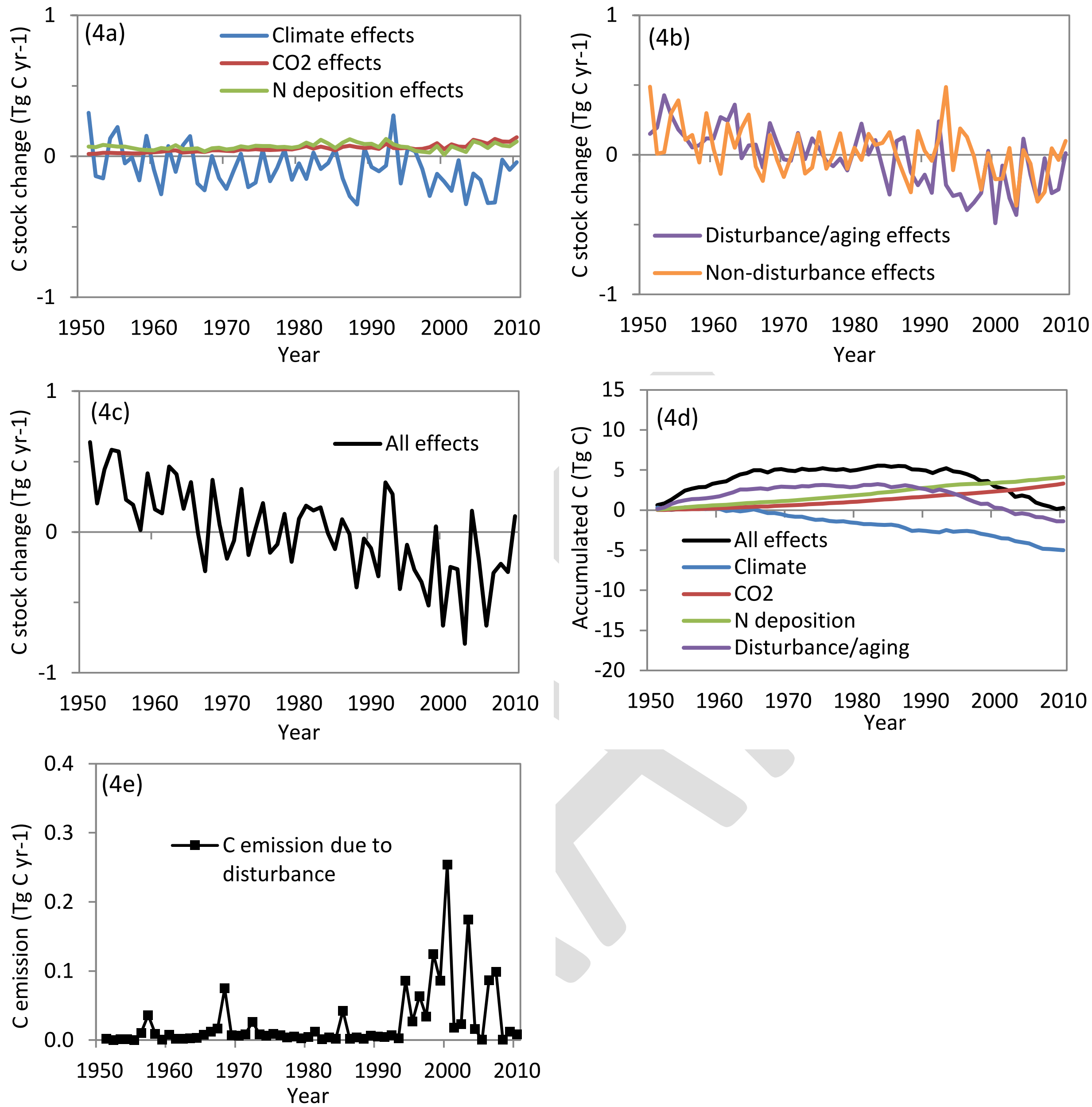


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.7 Idaho Panhandle National Forest - Idaho

Forests in the Idaho Panhandle National Forest generally show a decreasing trend in changing carbon (C) stocks and a shift from a C sink to a source in the mid-1980s (Figure 4c) mostly following the effects of disturbances and aging (Figure 4b, d). The stand age distribution shows the forest is mostly older, with a distinct peak in establishment 70-110 years ago (1900-1940), likely due to recovery after the last major fires before the onset of fire suppression and/or disturbances associated with Euro-American settlement in the region. Fire suppression also allowed the stands to continue re-growing rather than being disturbed by fires through much of the 20th century. Through the 1950s and 1960s, many of these stands were still growing at their peak productivity (Figure 2), thus contributing to the C sink, but have since aged and productivity has declined, causing forests to switch to a C source (Figure 4b-c) as decay and decomposition losses were greater than C gains. Recent fires, insects, and harvests were quite small or low-severity (Appendix A, Figure 1b) thus did not greatly affect the age structure or disturbance/aging effects, or cause significant, immediate C emissions (Figure 4b, e). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Appendix A, Figure 2b). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused greater C emissions and a stronger C source than the InTEC results indicate. Overall, disturbance/aging had the greatest positive impact on C accumulation from 1950-2010, but this rate of accumulation has been steadily declining since the mid-1980s (Figure 4d).

Of the non-disturbance factors, climate has had a mostly negative effect on C stocks since the late 1950s, while increased nitrogen (N) deposition (Figure 3c) and atmospheric CO_2 concentrations show positive effects (Figure 4a, d). The negative climate effects and positive CO_2 and N deposition effects mostly offset each other such that total accumulated C since 1950 is almost entirely a function of disturbance and aging effects (Figure 4d). Idaho Panhandle NF experienced a net gain of approximately 4.4 Tg C in C stocks from 1950 to 2010 (Figure 4d). When taking into account potential C losses due to recent disease impacts (Appendix A, Figure 2b), Idaho Panhandle NF may have experienced a small net loss in total C stocks.

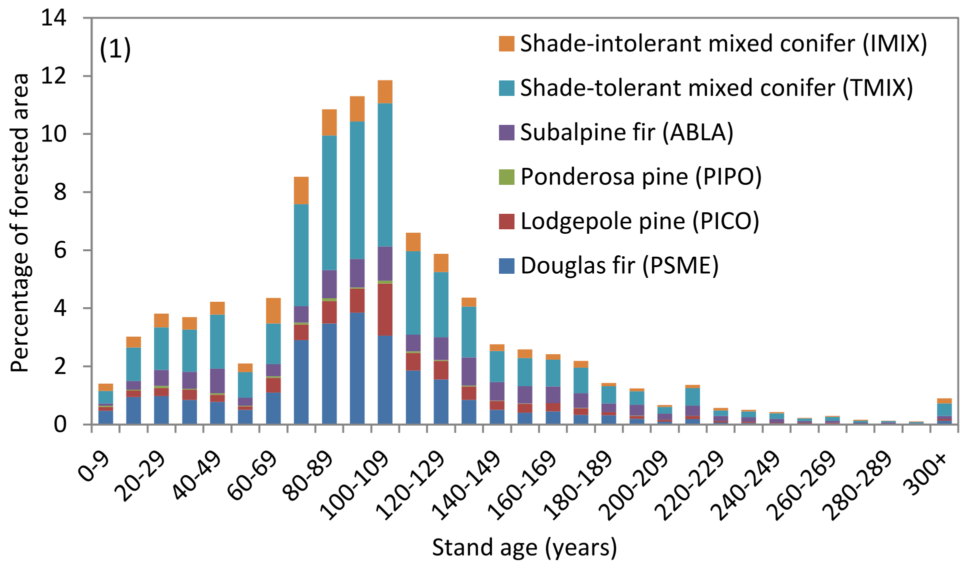


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

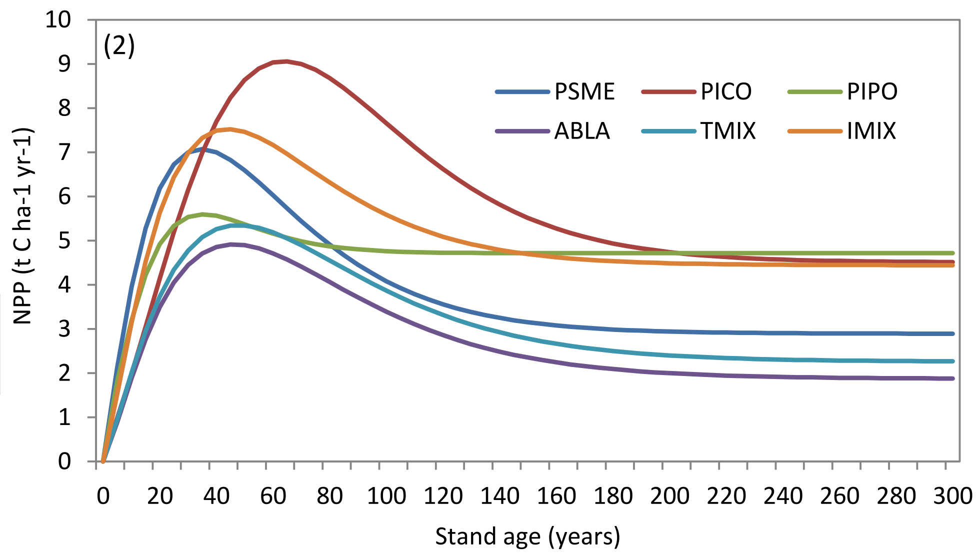


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

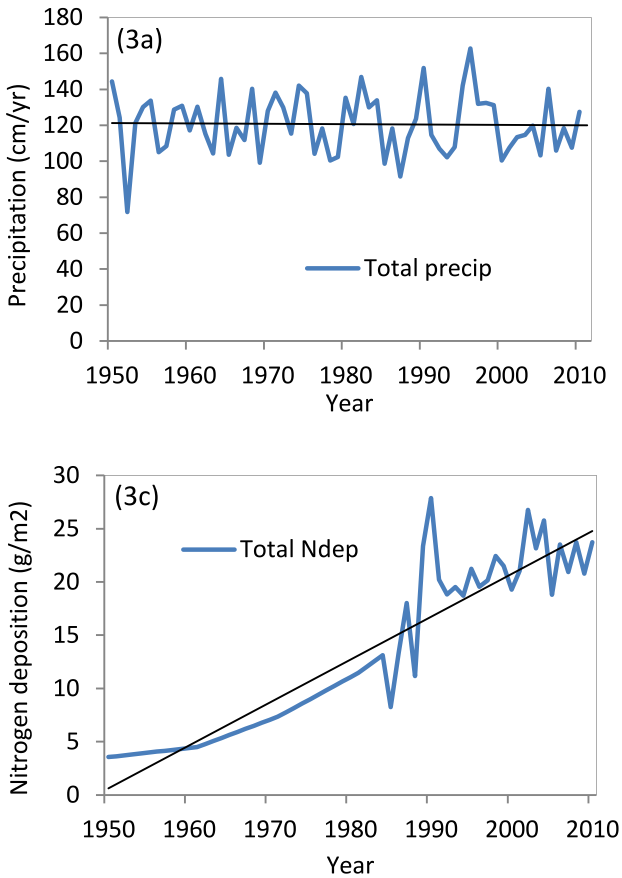


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

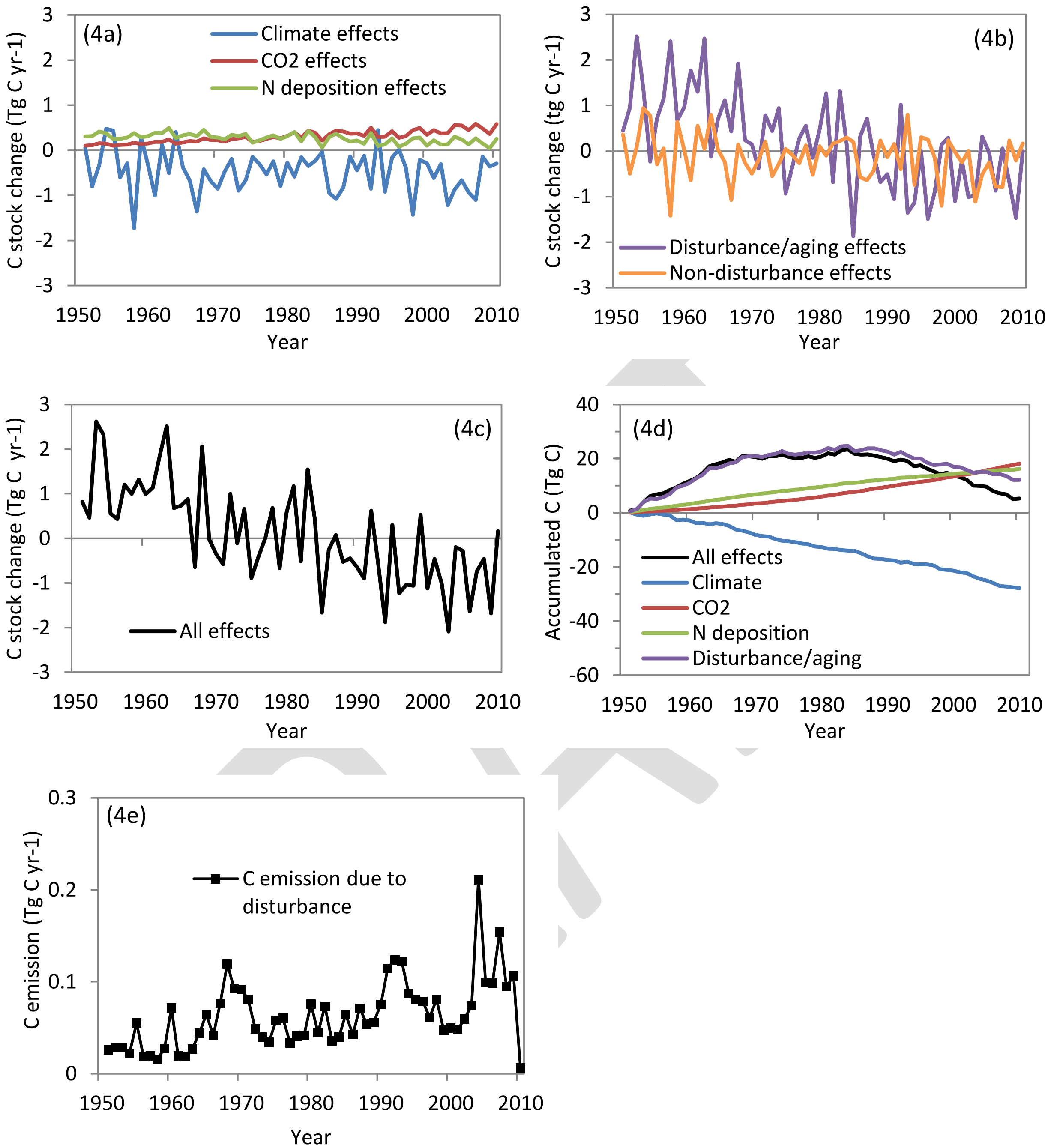


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.8 Kootenai National Forest – Montana & Idaho

Forests in the Kootenai National Forest fluctuated between a carbon (C) sink and a source from 1950-2010, but generally show a decline due to disturbance/aging and climate effects (Figure 4a-d). The stand age distribution shows a large pulse of stands that were establishing 100-109 years old (1900-1910) (Figure 1), likely due to recovery after the last major fires preceding fire suppression and/or disturbances soon after Euro-American settlement in the region. Fire suppression, beginning in the early 1900s would have also allowed these young stands to survive and continue to re-grow in the absence of fire. This pulse of mostly Douglas fir and Shade-tolerant mixed conifer stands would have reached peak productivity at about 30-55 years old (1930-1955)(Figure 2), explaining the C sink and positive C accumulation due to disturbances/aging through the 1950s and 1960s (Figure 4b, d). Despite the several moderate to severe disturbances, mostly harvests and fires, over the past few decades (Appendix A, Figure 1c), there has been minimal re-establishment (Figure 1), likely because these disturbances were quite small, affecting less than 1% of the forested area. The most significant disturbance years were 1992, 1994, and 2000 (Appendix A, Figure 1c) which caused increased direct C emissions (Figure 4e) contributing to the C source (Figure 4c). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Appendix A, Figure 2c). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger C source than the InTEC results indicate.

Climate has had a mostly negative effect on C stocks since the late 1950s with a few years of positive influence (Figure 4a, d). The trend of warmer temperatures (Figure 3b) and decreased precipitation (Figure 3a), cause increased soil respiration and constrained growth. The increases in nitrogen deposition (Figure 3c) and atmospheric CO_2 enhanced the C sink causing an accumulation of C (Figure 4a, d), but were overshadowed by the C losses due to disturbances/aging and climate. Overall, Kootenai NF experienced a net loss of approximately 24.5 Tg C from 1950-2010 (Figure 4d). When taking into account potential C losses due to recent disease impacts (Appendix A, Figure 2c), Kootenai NF likely experienced a larger net loss in total C stocks.

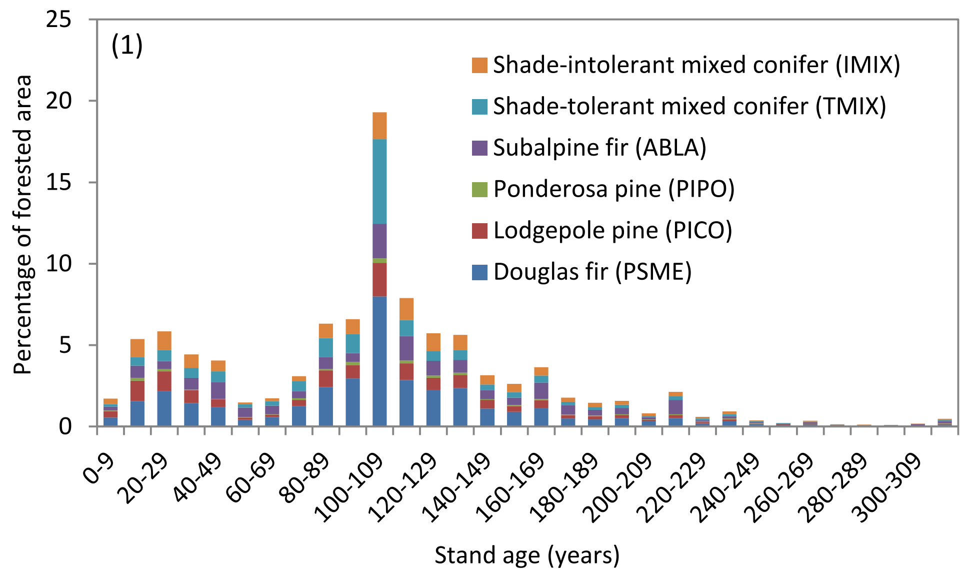


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

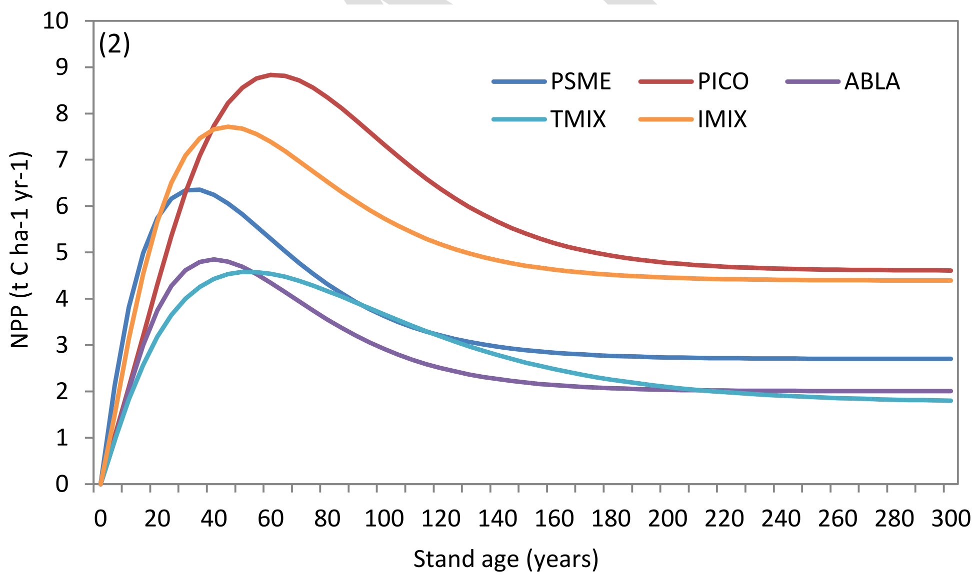


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX). Note: There was not an adequate sample of Ponderosa pine (PIPO) plots to derive NPP-age curves, thus the IMIX curve was used for any PIPO stands.

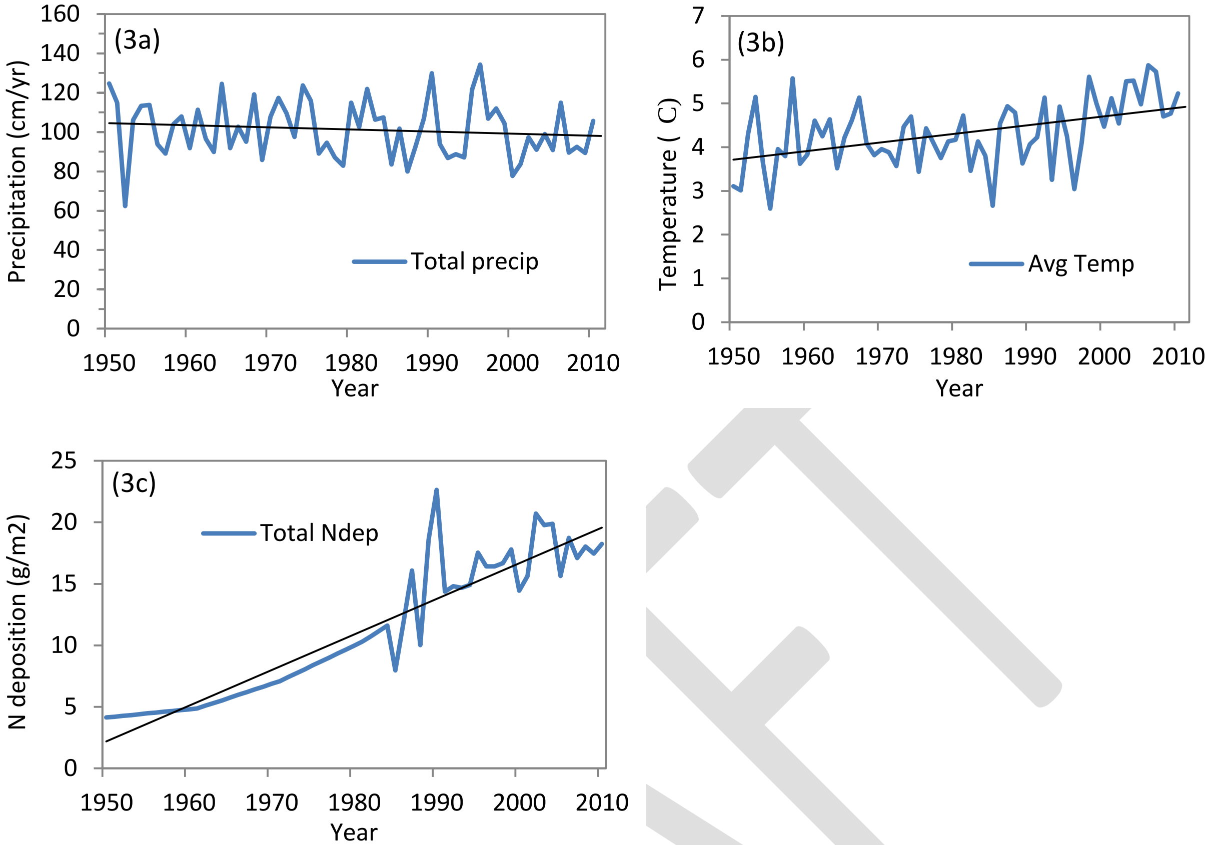


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

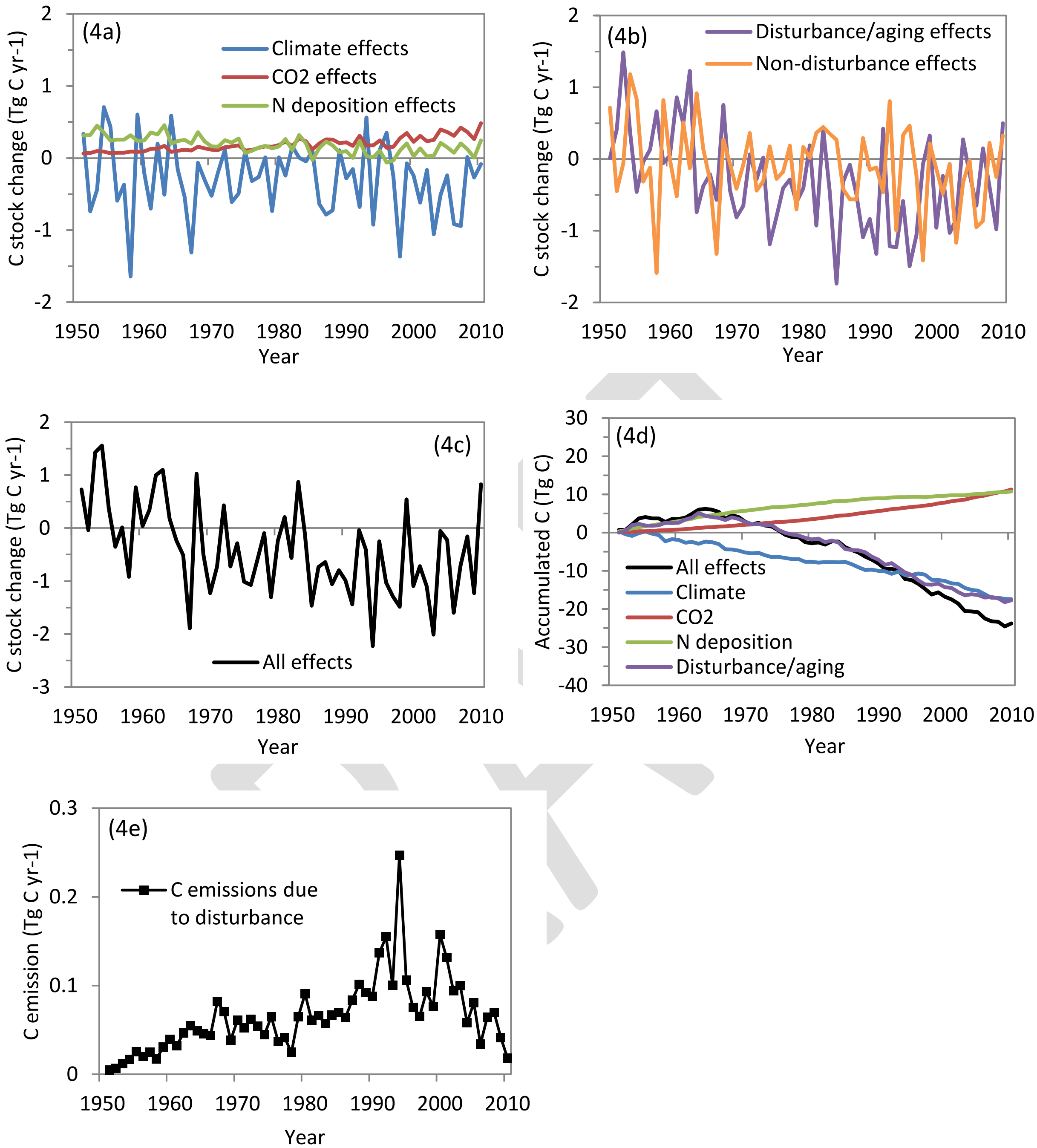


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.9 Lewis and Clark National Forest - Montana

Forest in the Lewis and Clark National Forest switched from mostly a carbon (C) sink to a source in the 1970s (Figure 4c) and C stocks have continued to decline through 2010 (Figure 4d). Increased disturbance and aging effects were responsible for this shift, though unfavorable climate conditions also played a role (Figure 4c). The stand age distribution shows that most stands are middle-older age, with a pulse of stands establishing 80-109 years ago (1901-1930) (Figure 1), likely as a result regrowth following the last major fires preceding the onset of fire suppression and/or disturbances associated with Euro-American settlement in the region. Fire suppression may have then allowed these stands to survive and continue to regrow, rather than being disturbed by fire. This pulse of mostly Douglas-fir forests would have reached maximum productivity (Figure 2) between the 1930s and 1960, which corresponds to period when forests were still a C sink (Figure 4b-c), and C stocks increasing (Figure 4d). Though most forests are older with declining rates of productivity, a large pulse of young stands <20 years old (Figure 1) have the potential to cause greater C accumulation and productivity in coming decades as they reach middle ages (Figure 2). These young stands are a result of post-disturbance recovery from major disturbances like the large high-severity fire in 2007 (Appendix A, Figure 1k), which also caused an immediate pulse of C emissions (Figure 4e).

Climate has generally had a negative effect on C stocks since the late 1950s (Figure 4a, d). A trend of warmer temperatures (Figure 3b) and decreased precipitation (Figure 3a) enhanced the negative climate effect, especially during the early-mid 2000s. Warmer temperatures increase soil respiration while droughts cause water stress, limiting growth. The increases in nitrogen deposition (Figure 3c) and atmospheric CO_2 enhanced the C sink (Figure 4a), but were not able to offset the C losses due to disturbances/aging, and climate. Forests in the Lewis and Clark NF experienced a net loss of approximately 16 Tg C from 1950-2010 (Figure 4d).

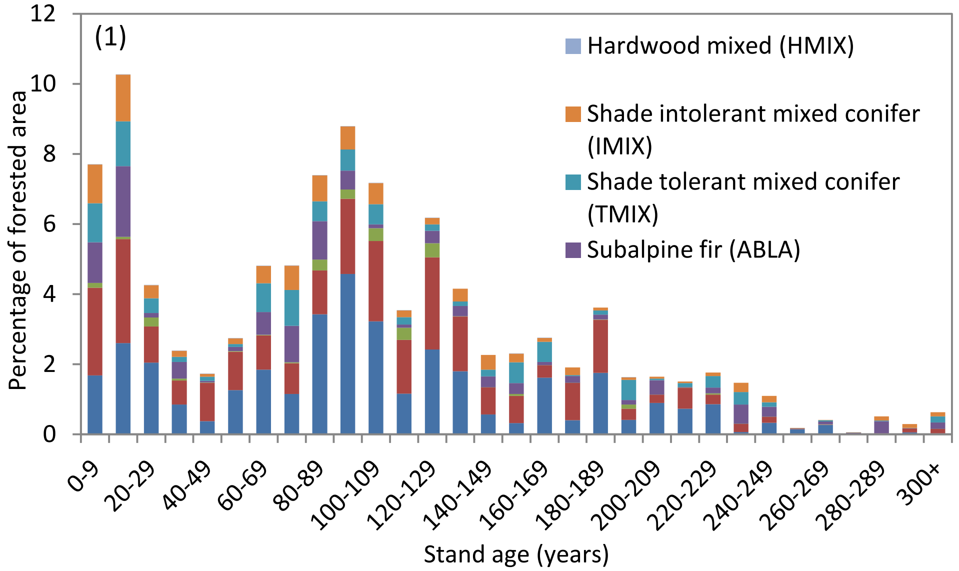


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

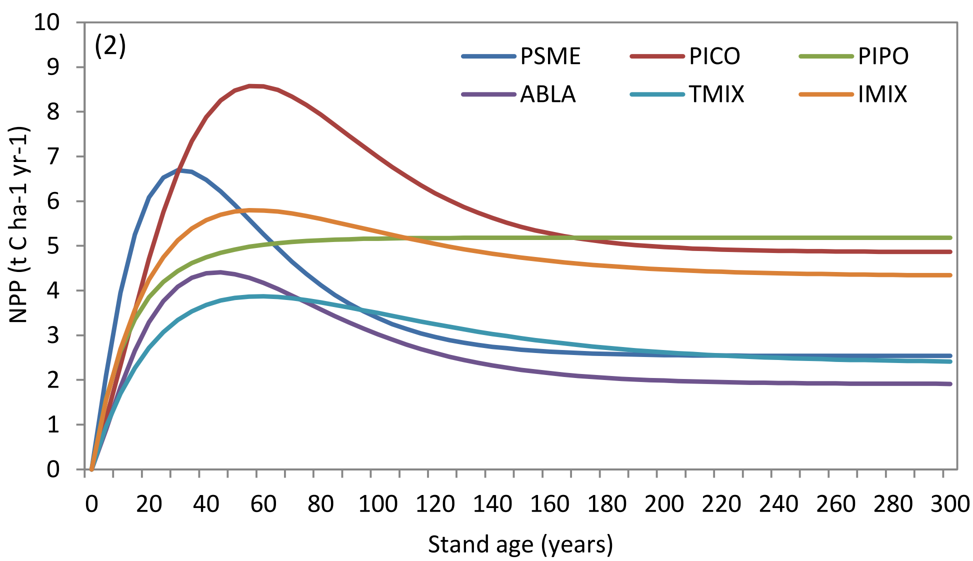


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

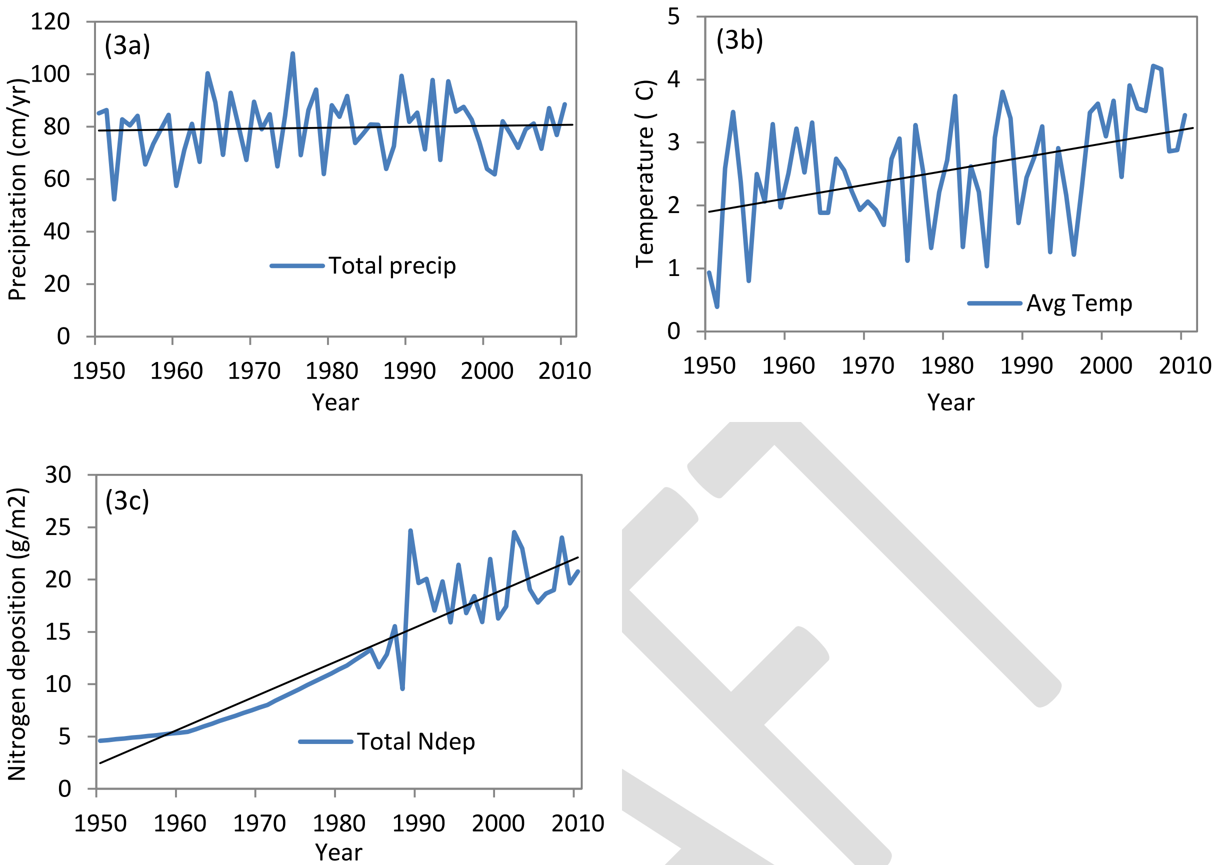


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

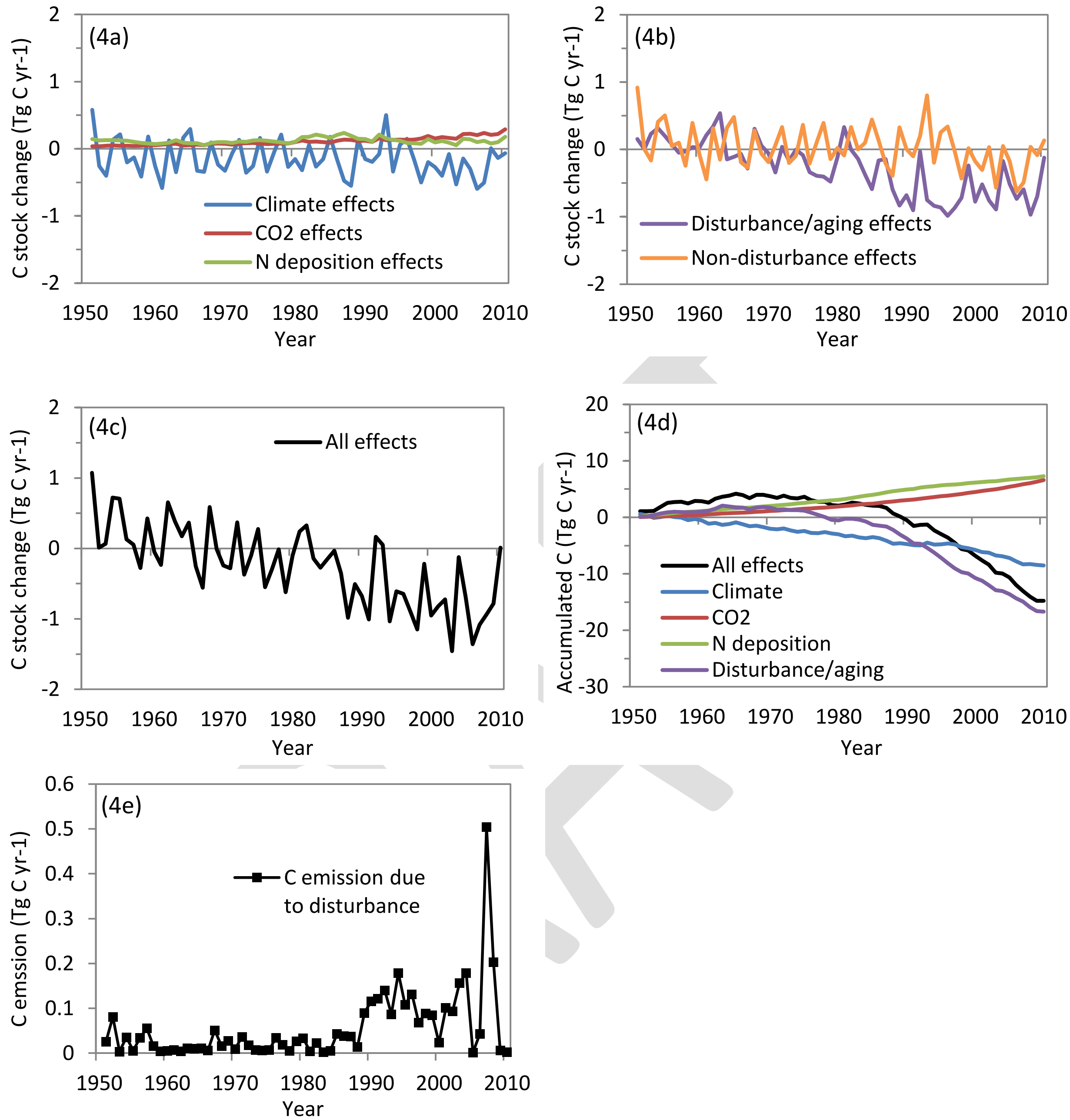


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.10 Lolo National Forest - Montana

Forests in the Lolo National Forest fluctuated between a carbon (C) sink and a source from 1950-2010, but generally show a decline in changing C stocks due to negative disturbance/aging and climate effects (Figure 4a-d). The negative disturbance and aging effect is supported by the stand age distribution, which shows a pulse of stands 90-109 years old that were establishing from 1901-1920 (Figure 1), likely as a result of recovery from the last major fires before fire suppression began and/or early settlement disturbances. Fire suppression may have also allowed these stands to survive and continue growing in the absence of subsequent fire disturbances. These mostly Douglas fir stands would have reached their highest rates of productivity when they were 30 years old or around 1930 through 1960, which corresponds to when disturbances/aging supported the C sink (Figure 4b) and when C stocks were increasing (Figure 4d). There is also a pulse of young stands 0-20 years old, which established after recent moderate to high severity disturbances, such as larger fires in 2000, 2004, 2007, and 2008 (Appendix A, Figure 1d). As these young stands enter middle-age, they will be most productive (Figure 2), and forests may continue to experience a C sink as happened in 2010 (Figure 4c). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Appendix A, Figure 2d). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger or more consistent C source since 1990 than the InTEC results indicate.

Climate has had more of a negative effect on C trends since 1950 (Figure 4a, d). A trend of warmer temperatures (Figure 3b) and decreased precipitation (Figure 3a) enhanced the negative effect of climate in the early-mid 2000s. Warmer temperatures increase respiration while droughts cause water stress, impeding growth. The increases in nitrogen (N) deposition (Figure 3c) and atmospheric CO_2 concentrations also enhanced the C sink (Figure 4a) and caused forests to accumulate C (Figure 4d). Despite the growth enhancements from CO_2 fertilization and N deposition, forests in the Lolo NF experienced a net loss of approximately 5.5 Tg C (Figure 4d) between 1950 and 2010. When taking into account potential C losses due to recent disease impacts (Appendix A, Figure 2d), Lolo NF likely experienced a larger net loss in total C stocks.

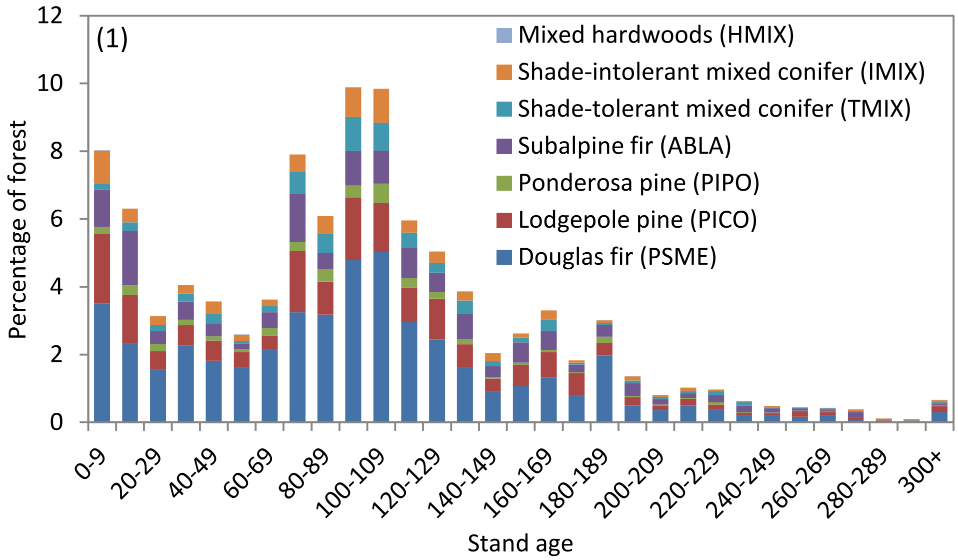


Figure 1. Age class distribution in 2010 displaying the percentage of forested area of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

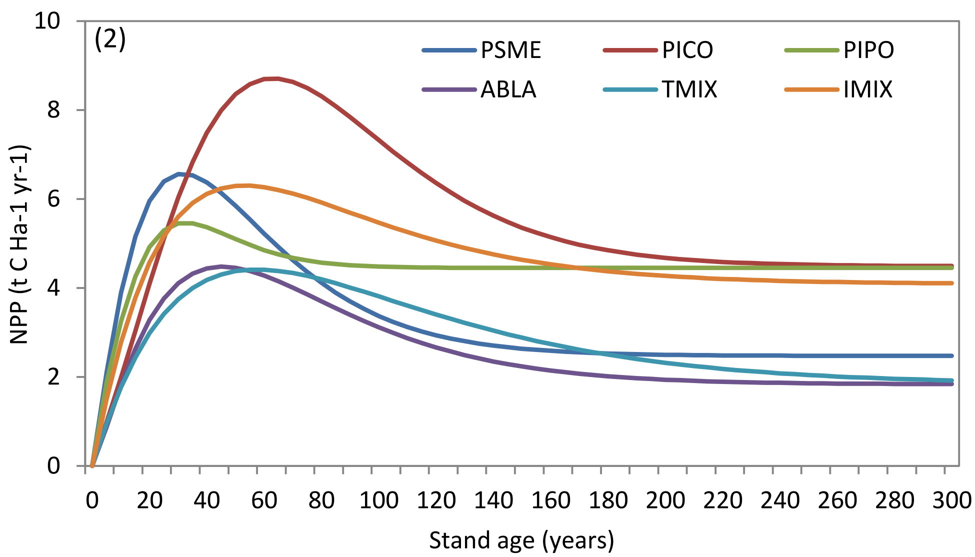


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

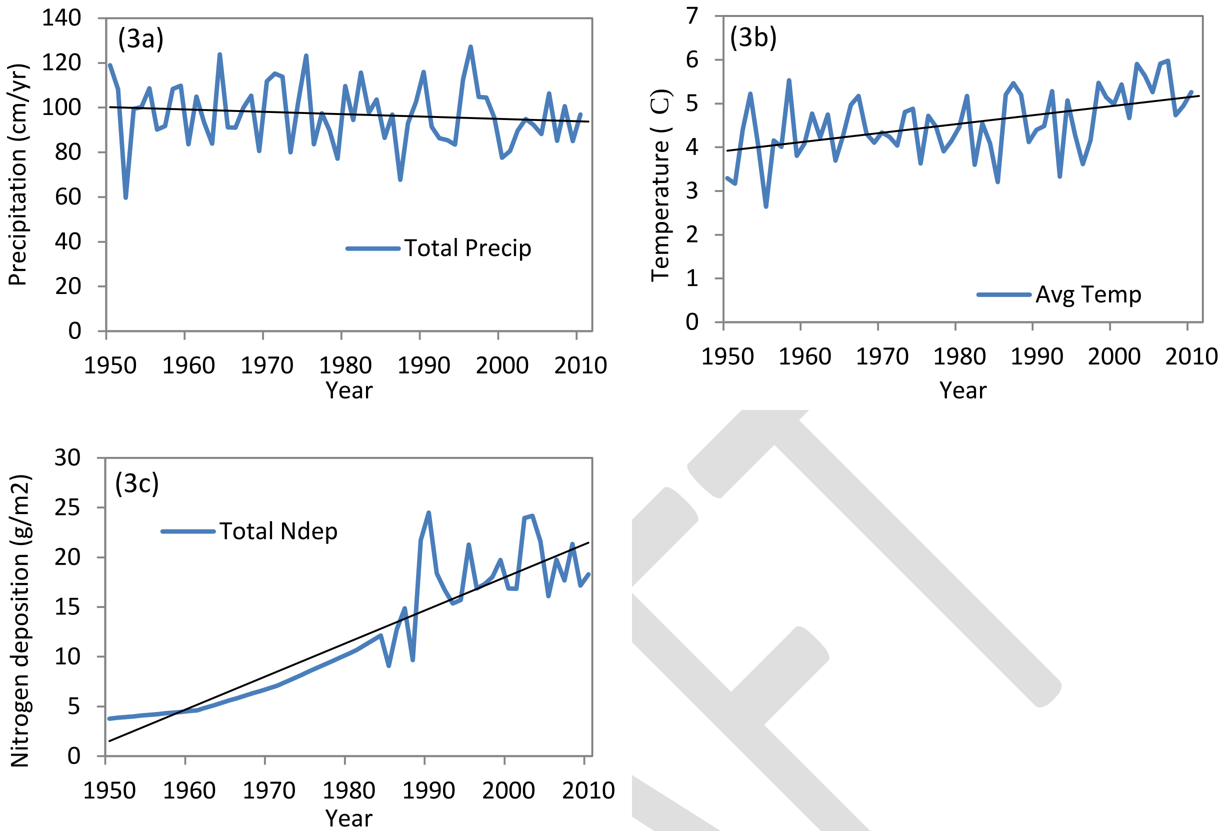


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

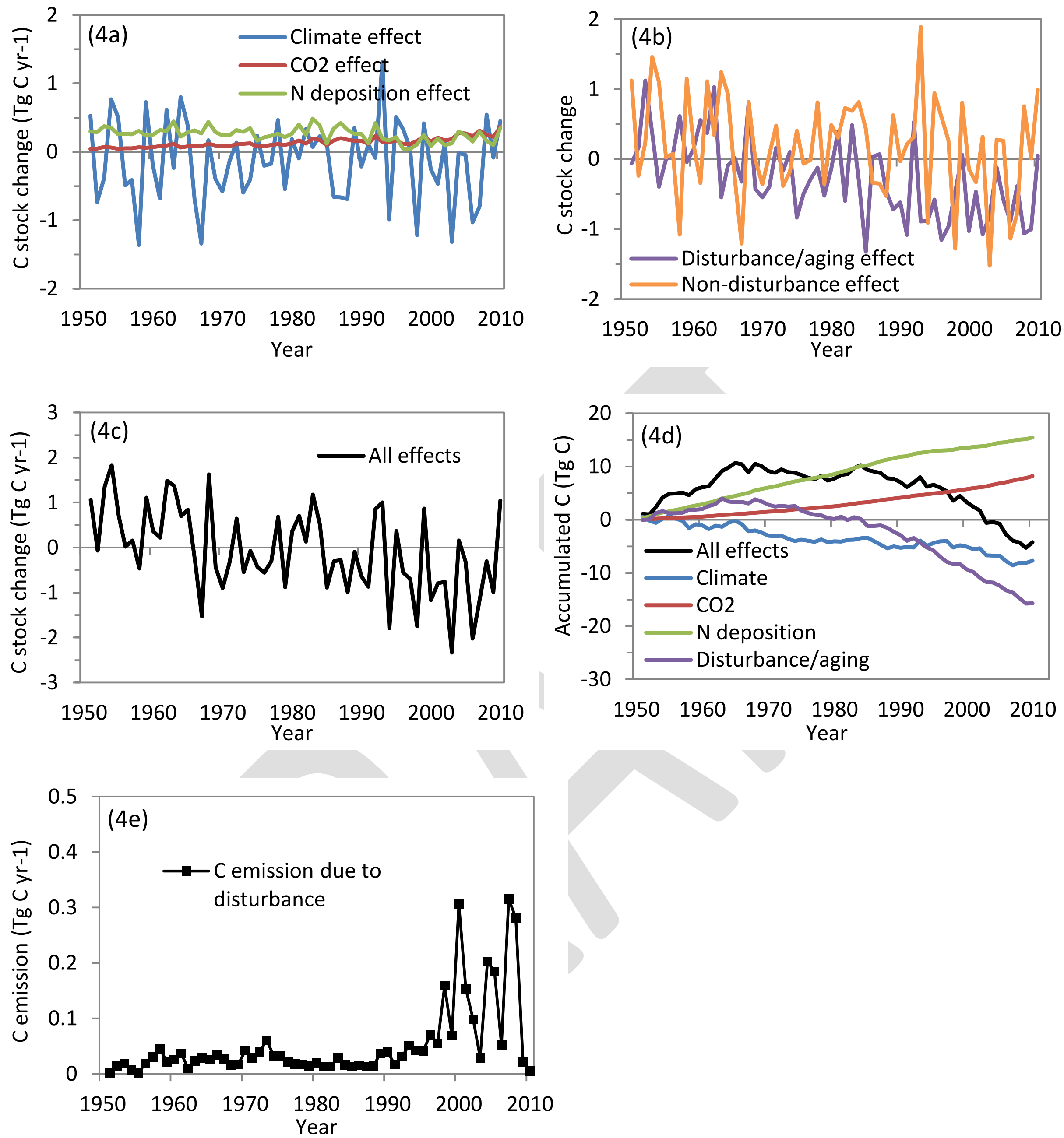


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.

C.11 Nez Perce-Clearwater National Forests - Idaho

Forests in the Nez Perce-Clearwater National Forests changed from a C sink to a source in the mid-1980s (Figure 4c) due to disturbance and aging effects, and to a lesser extent climatic effects (Figure 4a-b). In 2010, roughly 40% of the stands were between 70-109 years old (Figure 1), following establishment between 1901 and 1940, likely as a result of recovery from major fires and/or disturbances associated with EuroAmerican settlement in the region. Fire suppression, beginning in the early 1900s may have also allowed these young stands to survive and continue to re-grow without fire disturbances. This pulse of stands consisting of mostly shade-tolerant mixed conifer (TMIX) forests followed by Subalpine fir and Douglas fir forests, would have been most productive when they were roughly 35-55 years old (Figure 2), or throughout much of the mid-20^{th} century. These stand age characteristics corroborate forests being a C sink (Figure 4b) and accumulating C (Figure 4d) through the 1950s-1980s as a result of disturbance and aging effects.

The stand age distribution also shows a smaller pulse of trees that were established between 1990 and 2000, which may be a result of recent disturbances (Appendix A, Figure 1e). The forest experienced larger fires in the mid-2000s but these were mostly low-moderate severity thus did not cause significant mortality or subsequent stand establishment (Figure 1). Immediate C emissions due to disturbances increased in the 1990s through 2010 (Figure 4e), also explaining the transition to a C source during this time period (Figure 4c). However, the ForCaMF model results indicate that disease significantly reduced C storage over the past two decades (Appendix A, Figure 2e). Thus, when including recent widespread disease disturbances, it is likely that disturbances caused even greater C emissions and a stronger or more consistent C source since 1990 than the InTEC results indicate.

Climate has had a mostly negative effect on changing C stocks and C accumulation since 1950 (Figure 4a, d). The greatest climate-induced decline in C was from the mid-1990s-2010 (Figure 4a, d) due to warmer temperatures (Figure 3b) and a decrease in precipitation (Figure 3a), which together increase respiration and cause water stress thus constraining growth. The increases in nitrogen deposition (Figure 3c) and atmospheric CO_2 enhanced the C sink (Figure 4a), helping to offset the negative disturbance/aging and climate effects, and causing the forest to accumulate more C (Figure 4d). Despite recent declines in C accumulation and the transition to more of a C source, forests in the Nez Perce-Clearwater NFs experienced a net gain of approximately 24 Tg C from 1950-2010. When taking into account potential C losses due to recent disease impacts (Appendix A, Figure 2d), Nez Perce-Clearwater NFs likely experienced a much smaller C gain or potentially a C loss.

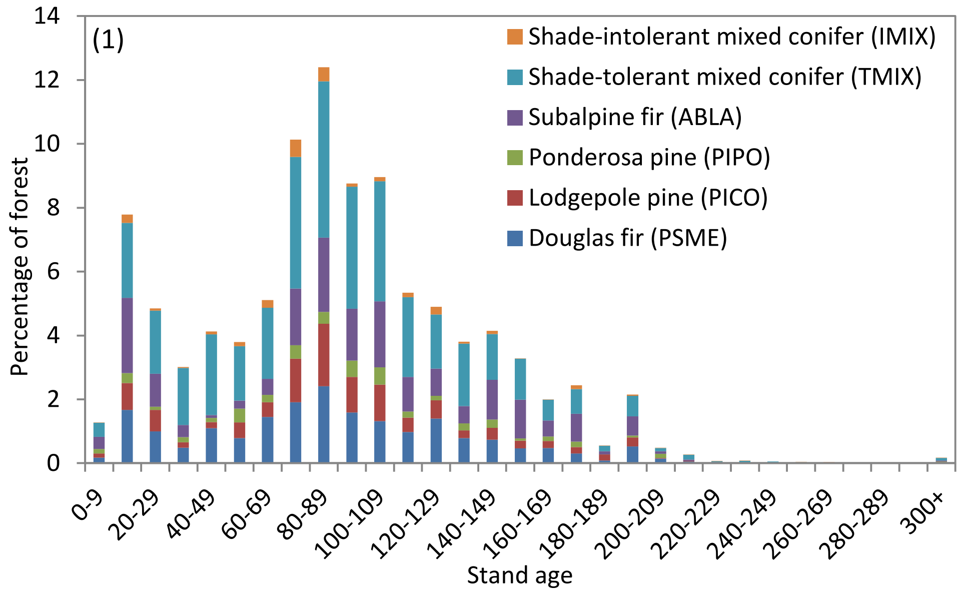


Figure 1. Age class distribution in 2010 displaying the percentage of forested of each forest dominance type in 10-year age classes. Dominance types are symbolized by stacked, colored bars that also correspond to the dominance types in Figure 2 below.

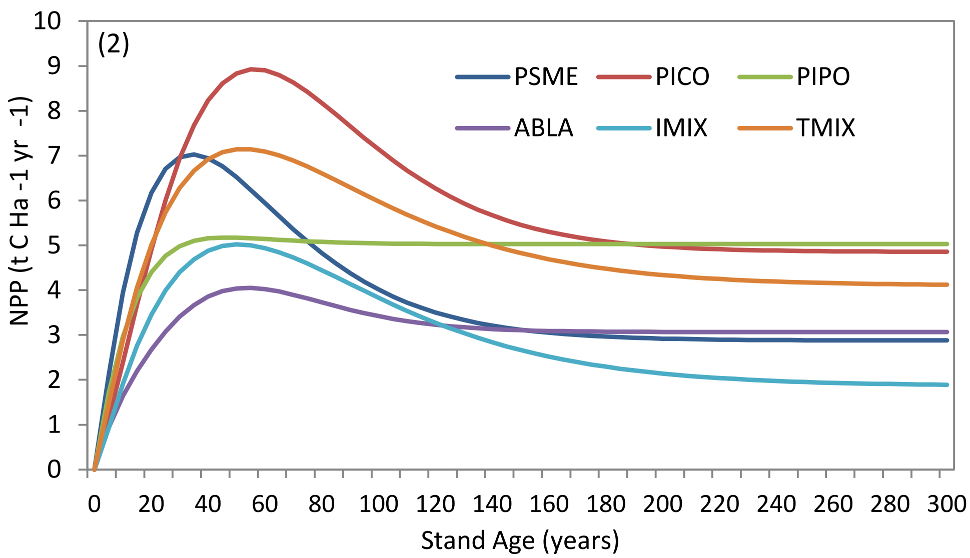


Figure 2. Relationship between net primary productivity (NPP) and stand age for each forest dominance type. Dominance types include: Douglas fir (PSME), Subalpine fir (ABLA), Lodgepole pine (PICO), Ponderosa pine (PIPO), shade-tolerant mixed conifer (TMIX), shade-intolerant mixed conifer (IMIX).

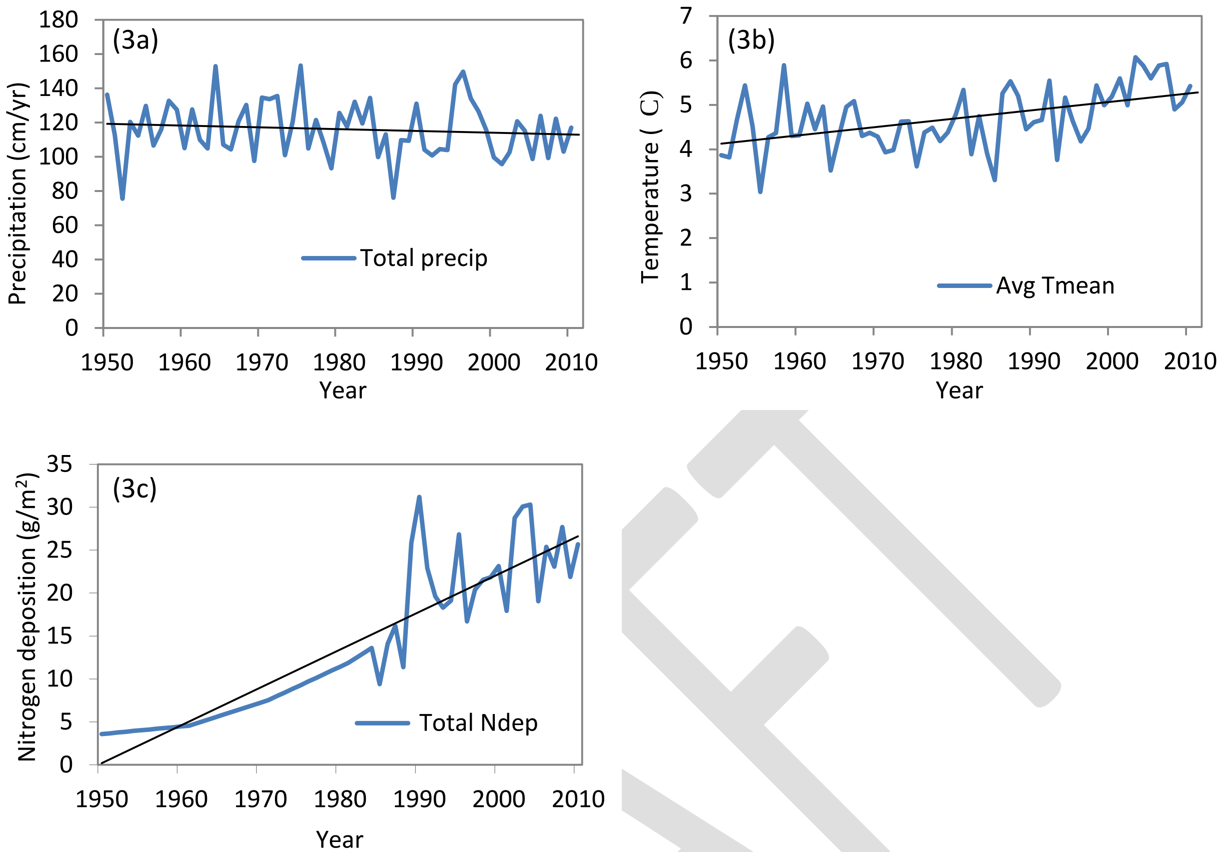


Figure 3. (a) Total annual precipitation (cm), (b) average annual temperature (°C), and (c) total annual nitrogen deposition from 1950-2010. Linear trend lines shown in black.

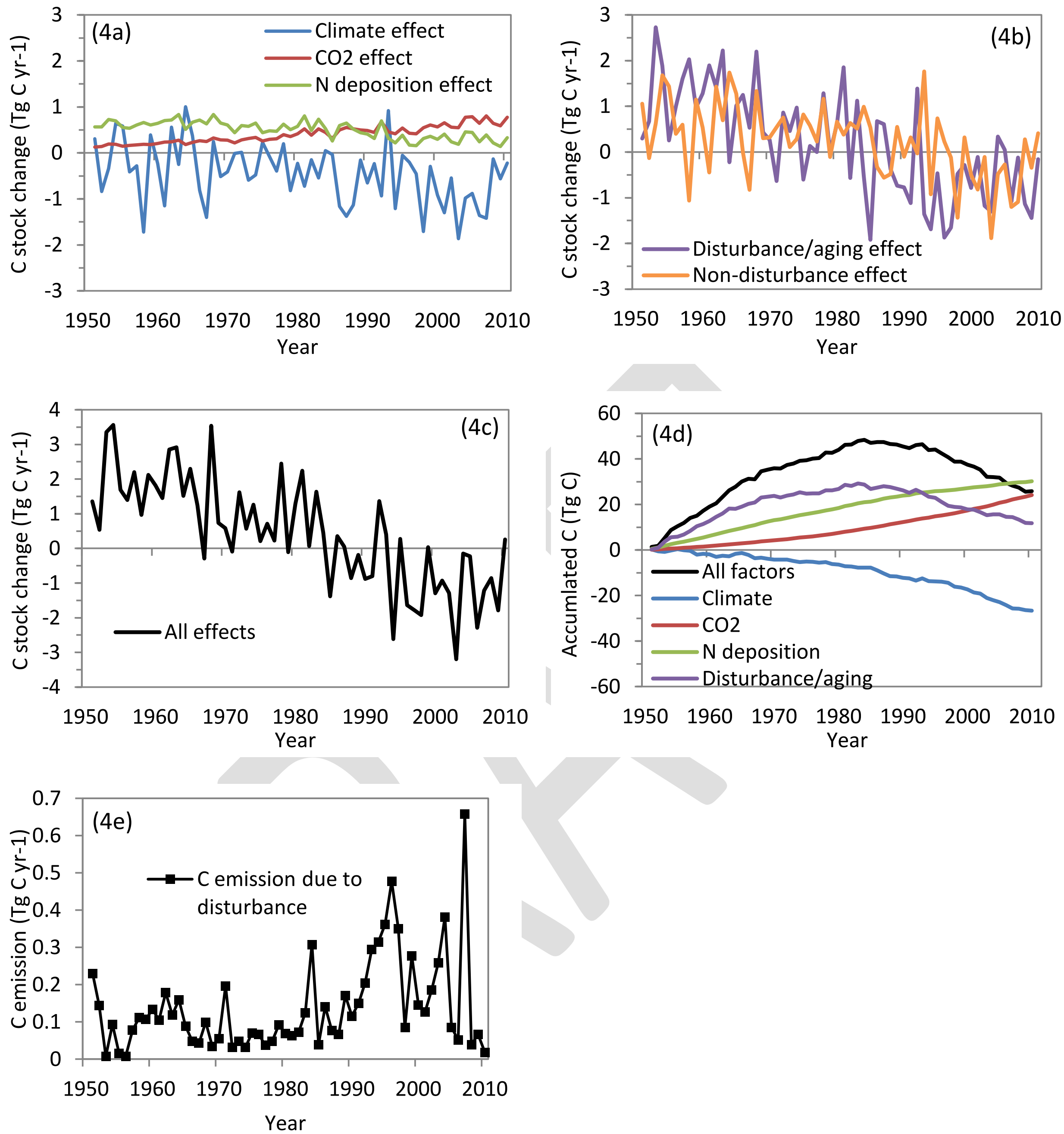


Figure 4. Changes in carbon stocks due to: (a) individual non-disturbance factors alone including climate variability, atmospheric CO_2 concentration, and nitrogen deposition; (b) all disturbance factors such as fire, harvest, and insects, as well as regrowth and aging and the sum of all non-disturbance factors combined; and (c) all factors combined which is the sum of disturbance\aging and non-disturbance effects; (d) Accumulated C due to individual disturbance\aging and non-disturbance factors and all factors combined from 1950-2010 excluding C accumulated pre-1950; and (e) C emissions due to disturbance events only. Positive values in Figures 4a-c represent C sinks from the atmosphere or enhancement effects, whereas negative values represent C sources to the atmosphere, or detraction effects.